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1990

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PREPARED BY THE

SUBCOMMITTEE ON SPACE

TRANSMITTED TO THE

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SCIENCE, SPACE, AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

ONE HUNDRED SECOND CONGRESS

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*Ranking Republican Member.

LETTER OF SUBMITTAL

House of Representatives,
Committee on Science, Space, and Technology,
Washington, DC, February 12, 1991.

Hon. George E. Brown, Jr.,
Chairman, Committee on Science, Space, and Technology,
House of Representatives.

Dear Mr. Chairman: This publication contains various reports submitted to Congress by NASA during the second session of the 101st Congress.

These reports are responsive to the Committee's requests as iterated in various house reports and public laws.

I commend these reports to your attention.

Sincerely,

Ralph M. Hall, *Chairman,*
Subcommittee on Space.

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STATUS REPORT
ON NASA
ASSURANCE ASSESSMENT TECHNOLOGY

George A. Rodney
Associate Administrator
Office of Safety, Reliability, Maintainability, and Quality Assurance
National Aeronautics and Space Administration

INTRODUCTION

NASA supports the use of Assurance Technologies to achieve mission and operational success, specifically through the Office of Safety, Reliability, Maintainability and Quality Assurance (SRM&QA). The mandate of the Office of SRM&QA is a formal directive to perform independent assessments. To comply, the SRM&QA disciplines use assurance technologies to gain the information necessary to plan, direct, implement, and evaluate all NASA programs and projects. Assurance technology connotes an integrated technical and management approach to determining risk and the probability of mission and operational success. SRM&QA assurance can be characterized as:

• Safety:	use of design and engineering to eliminate hazards
• Reliability:	probability that system will perform satisfactorily for the required time
• Maintainability:	continued satisfactory performance (also, restored performance to the desired level after maintenance)
• Quality:	the final product operates at the specified level of performance

The technical assurance function consists of multi-discipline (SRM&QA) assessments using both qualitative and quantitative (statistical) tools and techniques. Qualitative methods such as fault-tree analyses provide the basis for the initial assessment of probability of success. The quantitative techniques are used to refine the qualitative engineering assessment of the likelihood that a component, product, or program will perform as expected. Various numerical techniques for probabilistic risk assessments are currently available and being used within the NASA organization.

The managerial function, which can be referred to as Product Assurance, encompasses the entire program process: design, development, test, manufacturing, assembly, inspection, and operational phases. It entails oversight and assessments of program cost, schedule, and performance parameters; and the trade-offs that invariably occur.

NASA uses risk management/assurance and risk assessment methodologies in both the Space Shuttle and Space Station programs to supplement the qualitative assurance measures of hazard analyses, and failure mode and effects analyses (FMEAs). NASA defines the risk assessment process as qualitative categorization or quantitative estimation of risk, followed by an evaluation of risk significance. Risk management entails balancing risk with cost, schedule, and other programmatic considerations.

QUANTITATIVE ASSESSMENTS

NASA's complex system requirements necessitate engineering/analytical techniques that are flexible enough to be used in assessing risks to existing programs (e.g., tile damage on the Space Shuttle fleet) as well as identify potential problems in new programs (e.g., the behavior of fire in microgravity). Numerical data drive the powerful computer simulations, laboratory mockups, and mathematical models that NASA uses to deduce design and operational requirements for products and projects untested by actual mission use.

NASA quantitative assessments are rigorous engineering reviews that use reliability data and projections of risk occurrences to calculate the numerical probabilities of risk to personnel and mission. These evaluative techniques are used by NASA SRM&QA engineering at various stages of a process or program. For example, a design engineer and a safety engineer may both use a fault tree to determine potential weak points in a design to identify areas where redundancy or increased structural capacity would improve the safety by minimizing the probability that a critical event (failure) will occur.

Fault-tree analysis is a graphical, deductive method used by NASA to support detailed system analyses and the decision-making process. This analysis enables design or safety engineering to assess combinations of possible undesired events (failures) or specific hazards to personnel or mission. The fault-tree technique begins with a qualitative engineering assessment of a system event that, subsequently, can be used for a quantitative system evaluation. The quantitative evaluation determines the probability that an event will occur, the significance or importance of the event, the baseline level of safety (also used to determine effects of design changes), and fault tolerances.

Design engineering uses mathematical techniques for a myriad of concerns. For example, worst-case analyses are used to examine critical design parameters that are subject to tolerances, aging, and environmental stresses. The design engineer evaluates the impact of worst-case tolerances and part variations in combination with environments to which the part is exposed to determine the maximum impact on a product.

Quality Assurance presents a clear challenge for assurance technology applications. Given the objective of maintaining specified levels of performance and quality, NASA must determine ways to assess improvements to products and processes. Similar to other government agencies and organizations in the private sector, NASA is involved in an ongoing effort to develop effective measurands for quality. Currently, quality is

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Quality Assurance presents a clear challenge for assurance technology applications. Given the objective of maintaining specified levels of performance and quality, NASA must determine ways to assess improvements to products and processes. Similar to other government agencies and organizations in the private sector, NASA is involved in an ongoing effort to develop effective measurands for quality. Currently, quality is viewed as a function of safe, reliable, and maintainable performance at or above specified levels or within quantified guidelines (such as factor of safety criteria).

The newly established SRM&QA Technical Standards division for Applied Technology builds on the premise of quality as a function of safety and reliability. This new division will focus the efforts of disciplines that are involved in hardware design and development. The division is positioned to support NASA's increasingly sophisticated requirements through establishing and maintaining Agency-wide standards and methods for those applied technologies that are required to design, develop, manufacture, assemble, test, and operate safe and reliable hardware. In this context, quality is more amenable to statistical analysis. Quantitative tools and techniques such as nondestructive evaluation (NDE) are used to project operational success.

NDE provides a nonintrusive means of evaluating system elements (parts, materials, structures, and human factors); it enables the engineer to evaluate physical properties/behavior (such as impact toughness, sensitivity) without affecting the area being examined. One application of this technique for the Space Station Freedom would be to estimate corrosion, fatigue or impact damage over extended duration operation. NDE techniques such as computer-aided tomography (3-dimensional imaging) are used in engineering assessments; for example, to determine the capability of a structural component or human muscle to function properly after extended duration missions in a zero-g environment.

Tomography is an example of evaluative techniques that NASA can use in maintaining spacecraft on-orbit. Earth-bound engineers in ground stations use sophisticated computer processes to predict or identify potential hazards and determine preventive/corrective measures, relying on data (such as downlinked digitized images) obtained directly from the spacecraft. Other NDE applications include interferometric methods such as real-time holography/shearography, which may be used to inspect pneumatic tires for ply separations as well as to investigate composite structures and bondlines.

PRODUCT ASSURANCE

NASA product assurance focuses reliability and quality assurance expertise to meet design goals and operational requirements. Product assurance is involved in each developmental phase for a part or product, from initial concept/design through manufacturing and operation. The objective of product assurance is to enhance system performance and extend the life expectancy of the system or product. Design and reliability engineers use qualitative and quantitative analysis techniques to address such issues as redundancy and wearout factors for parts, materials, and processes. In addition to fault-tree and worst-case analyses, product assurance also relies on tools such as reliability prediction, and Parts Derating and Stress Analysis. Design and reliability engineers use the prediction technique to assess the impact of the design on reliability and identify areas of design deficiency. The Parts Derating and Stress Analysis enables the design engineer to evaluate stress-to-strength ratios for each component or part to minimize the probability of stress-related failures. A derating factor is selected for each parameter (thermal, electrical, and mechanical) or component and the product is designed so that components operate under reduced stress.

RISK MANAGEMENT/RISK ASSESSMENT

NASA has instituted a comprehensive risk management/risk assessment program at Headquarters and the individual field centers as specified in NASA Management Instruction (NMI) 8070.4. This NMI establishes the roles, responsibilities, and methodology for evaluating risk. NMI 8070.4 stipulates the Agency objective to use quantitative assessments as appropriate, particularly for new programs. NASA risk evaluation methods include classical and Bayesian statistical quantification using a variety of logic models (such as faults trees and event trees). Risk diagrams are used to portray the frequency of occurrence of failure scenarios (with uncertainties) versus damage levels. The risk diagrams are integrated into quantitative risk decision models, considering cost, performance, and damage.

INTEGRATED APPROACH

Product assurance efforts for the Space Station Freedom (SSF) program exemplify how the SRM&QA disciplines successfully integrate their expertise and techniques to form the assurance concept. The Office of SRM&QA has been actively involved in the initial planning for the space station. SRM&QA personnel have developed SSF safety and product assurance requirements definition documents. SRM&QA personnel also have developed trend analysis requirements for problem, performance, supportability, and programmatic indicators. SRM&QA oversight assures that space station elements--including parts, materials, and processes--will operate reliably and to approved specifications. Part of this function is to develop NDE methods for structural flaw detection. Oversight also assures that these elements can be maintained or, if necessary, repaired to normal working condition. The Office of SRM&QA performs independent validation and verification, encompassing varied functions such as ensuring that components pass all required inspections and monitoring production processes (for example, to check for statistical variances).

CONCLUSION

NASA is applying assurance assessment technology through the Office of Safety, Reliability, Maintainability and Quality Assurance. The SRM&QA disciplines comprise an integrated approach to assurance requirements. Increasingly, SRM&QA personnel are using quantitative analyses to assess risk to systems and programs; and to assist NASA program management in finding safe and equitable means of balancing mission requirements, schedule, and costs. To broaden the Agency's experience base in these assessment techniques, the Office of SRM&QA is developing quantitative risk assessment training courses, primarily for use at the field centers.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

APR 12 1990

Honorable Robert A. Roe
Chairman
Committee on Science,
Space and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

I am pleased to provide the enclosed CRAF/Cassini cost containment plan pursuant to direction contained in H.R. 3729, the NASA Multiyear Authorization Bill of 1989, as passed by the House of Representatives on November 21, 1989. Subsequent updates to the plan will be submitted biannually as requested. I believe that this plan will enable NASA to keep tight management controls on the CRAF/Cassini program and prevent any potential cost growth.

Sincerely,

Richard H. Truly
Administrator

Enclosure

cc:
Honorable Robert S. Walker

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
COMET RENDEZVOUS ASTEROID FLYBY (CRAF)/CASSINI
COST CONTAINMENT PLAN/REPORT
MARCH 1990

BACKGROUND:

This report is in response to Congressional direction in conjunction with action on the FY 90 budget directing NASA to submit a cost containment report on the Comet Rendezvous Asteroid Flyby (CRAF)/Cassini program.

House Report 101-297, the Conference Report accompanying H.R. 2916, the VA-HUD & Independent Agencies Appropriations Bill states:

> "The conferees expect NASA to submit with the FY 1990 operating plan the projected annual funding requirements for each year of development of the CRAF-Cassini program. Additionally, these annual funding requirements should be updated on January 31, and July 31 of each subsequent fiscal year based on the most recent data available, including the program operating plan (POP) results."

The Conference Report further stated that the Congress:

> "Will, however, "cap" each annual appropriation at such amount, provided that the accumulated sum of the amounts does not exceed $1,600,000,000. In the event that it is determined during the course of this program that the total budget will exceed $1,6000,000,000, NASA will be required to descope the program to fit within the total funding limit."

S. 916, the FY 1990 passed Senate authorization bill contains language which states:

> "A cost containment plan shall be submitted to the Committee on Commerce, Science and Transportation of the Senate and the Committee on Science, Space and Technology of the House of Representatives by January 31, 1990 and updated on July 31, and January 31, of each succeeding year until such funds are expended."

Similarly, Senate Report, 101-157 accompanying S. 916, the FY 1990 Senate Authorization bill states:

> "S. 916, as reported, authorizes $30,000,000 for the CRAF and Cassini missions if a cost containment plan is

> formulated for those missions and submitted to the Committee on Commerce, Science, and Transportation of the Senate, and to the Committee on Science, Space and Technology of the House of Representatives and to the Committees on Appropriations of the House and Senate. The Committee expects NASA to initiate formulation of this plan immediately. The Committee expects this plan to contain the annualized and total estimated cost of these missions. Failure to stay within a set percentage of the plan's funding profile would result in the termination of the CRAF mission."

Identical authorization bill language to that in S. 916 was included in H.R. 3729, the House authorization bill as passed on November 20, 1989.

INTRODUCTION

The CRAF/Cassini cost containment plan consists of a vigorous application of resource planning, managing, tracking and reporting procedures which are being followed by the Office of Space Science and Applications (OSSA). Rather than impose new management systems upon this program, we believe that, when stringently applied, tested OSSA technical and resource management techniques are superior to any other approach.

This document is structured in such a way as to provide a consistent format for each and every semi-annual report. In each category of OSSA Program Management activity, there will be a statement of the plan for CRAF/Cassini (Plan) followed by a status report (Status) which will indicate performance with respect to the plan for the current reporting period. Enclosure 1 is a listing of the relevant non-recurring milestones for the cost containment activities on both CRAF and Cassini.

I) PROJECT/PROGRAM DEFINITION & RECOMMITMENT

Plan:

As is the case with all major OSSA missions, a Non-Advocate Review (NAR) of the technical readiness and the basis of the cost estimates was required before submission of CRAF/Cassini as an FY 1990 New Start candidate to the NASA Administrator. In addition, NASA plans to periodically conduct comprehensive Cost Reviews involving formal external review board membership (similar to the NAR) in conjunction with major project milestones (Preliminary Design Review (PDR), Critical Design Review (CDR), etc.);

Status:

One of the reasons we are confident that we can deliver CRAF/Cassini for $1600M is due to the fact that the program is relatively mature. CRAF/Cassini has the benefit of six years of intensive definition studies and four non-advocate reviews on approach and cost. NASA has invested almost $100M through FY 1989 in the definition studies for this program. Although CRAF/Cassini is a complex program, CRAF/Cassini is well understood both programmatically and technically.

Enclosure 2 details the annualized and total estimated cost of the CRAF and Cassini missions. The cost profile complies with P.L. 101-144, dated November 9, 1989. It should be noted that programs of a highly technical nature such as CRAF/Cassini are subject to fluctuations in annual funding requirements. While the Office of Space Science and Applications (OSSA) has determined that the total funding provided is adequate to conduct the program, some flexibility should be allowed to rephase the overall funding profile to meet changing program requirements. As specified elsewhere in this document, these requirements will be reviewed periodically and will be addressed in future reports.

II) ORGANIZATION & STAFFING

Plan:

The commitment by senior agency management to appoint seasoned managers to complex and challenging programs such as CRAF/Cassini is another critical element of the cost containment plan. Experienced, senior NASA program management officials will be selected and assigned to CRAF/Cassini both for program management responsibility at NASA Headquarters and for project management responsibility at the Jet Propulsion Laboratory (JPL).

Status:

The CRAF/Cassini project organization at JPL has been in place since 1982 with Mr. Ron Draper (formerly the Galileo Spacecraft Systems Manager) designated as Project Manager since 1983. Many of the engineers who will work on CRAF/Cassini will be drawn from the experienced cadre developed over the course of the Galileo program. More recently, Mr. Howard Wright was appointed as CRAF/Cassini Program Manager at NASA Headquarters. Mr. Wright is a seasoned program manager as evidenced by his experience as former Deputy Project Manager for Viking, Director for Projects at Langley Research Center and, most recently, Deputy Program Manager in the Joint Air Force/NASA Program Office for the National Aerospace Plane (NASP).

III) INVESTIGATION SELECTION & CONFIRMATION

Plan:

Separate selection processes will be conducted for CRAF and Cassini. Resource assessments, both technical and fiscal, will be conducted as a part of the selection process. In addition, confirmation reviews will be conducted following instrument definition phase activities to assure the retention of adequate resources. Descoping plans will be developed and approved by all parties (program, project and science investigators) in order to assure coordination of actions necessary to contain cost. The "Descoping Plan" is a relatively new addition to the OSSA procedures for cost containment. This plan is intended to serve as a pre-negotiated contract among all parties affected identifying actions to be taken in the event that it is necessary to delete scope from the program. The first of these plans was developed for the Global Geospace Science (GGS) mission. A CRAF/Cassini Program Descoping Plan will be developed so that, if it is determined during the course of this program that the total budget will exceed the planned resources, NASA will be prepared to descope the mission to fit within the funding limit as indicated in Public Law 101-144 dated November 9, 1989.

Status:

The investigation selection process and the required resource requirements assessment were completed for CRAF in 1986, and were factored into the NAR. A listing of the selected CRAF investigations is provided as Enclosure 3. A similar process is planned for Cassini in the fourth quarter of FY 1990. The confirmation process for CRAF and Cassini are planned for 1991 and 1992 respectively according to the schedule in Enclosure 1.

Descoping options are currently being developed by the program and project managers together with the science team members. Given the various checks and balances that are discussed in this cost containment plan, the decision by the Associate Administrator for Space Science and Applications to invoke the descope option would only occur if it was apparent that the total budget authority for development of the two spacecraft through launch plus 30 days of the Cassini mission would exceed $1600M. It is our intent to finalize the list of descoping options concurrent with confirmation of the science investigations for the respective missions. The Associate Administrator for Space Science and Applications will retain this list for implementation as appropriate.

IV) PROGRAM REQUIREMENTS INTEGRATION

Plan:

CRAF/Cassini will utilize standard NASA procedures to assure coordination and documentation of all management commitments as well as project support requirements including the Program Approval Document (PAD), Project Plan, Flight Assignment Board (FAB), Support Instrumentation Requirements Documentation (SIRD), and Network Support Plan (NSP). These processes and the resulting documents will formally establish any agreements between the NASA Administrator and the Associate Administrator for OSSA, between the Associate Administrator for OSSA and other Program Associate Administrators, as well as those between Associate Administrator for OSSA and the JPL Project Office.

Status:

Both the PAD and the Project Plan are being developed. The Associate Administrator for Space Flight chaired a Flight Assignment Board meeting in the fourth quarter of FY 1989 which confirmed the assignment of CRAF and Cassini to Titan IV/Centaur vehicles in 1995 and 1996, respectively. The Network Support Plan has been completed, reviewed and concurred in by the Associate Administrators for OSSA and the Office of Space Operations (OSO). Preliminary work on the SIRD has begun.

V) PROGRAM REVIEW AND ASSESSMENT

Plan:

From the initial new start approval, the CRAF/Cassini program and project management teams have been aware that this project will be conducted under a high level of scrutiny and oversight. The program management structure has been designed to maximize visibility into several levels of detail, e.g. spacecraft subsystems, science instruments, and mission design. Not only will the program be analyzed at these levels, but by several levels of project and program management over various periods of time, including the Associate Administrator for Space Science and Applications and his Deputy, the Director of the Jet Propulsion Laboratory, the Assistant Laboratory Director for Flight Projects at JPL, the OSSA Director, Administration and Resources Division, and the OSSA Director, Solar System Exploration Division.

The Solar System Exploration Division's senior management conducts monthly reviews to address technical, scientific, schedule and resources status of major projects. In these reviews, monthly cost accruals are reviewed against the plan established by the OSSA Administration and Resources Management Division based on JPL Program Operating Plan (POP) data. Variances to the cost plan must be explained in detail including a strategy for recovery by the Program Manager. Significant information identified in these reviews is also presented at the monthly OSSA program review with the Associate Administrator.

In addition to the standard monthly reviews, the Deputy Associate Administrator for OSSA conducts quarterly reviews of all major flight projects. The project status is reported by the Flight Project Branch Chief, Program Manager and Program Analyst. CRAF/Cassini will be extensively reviewed in this forum, including the status of near term schedules, total resources planning (including reserve status), and nay issues or technical concerns which may significantly impact the program. Costs on each major spacecraft subsystem, individual science instrument, and mission operations element will be planned and monitored against the plan in these quarterly reviews, and subsequently reported in a summary fashion at the monthly reviews conducted by the Associate Administrator for OSSA. Monthly reviews are scheduled so as to allow the Associate Administrator for OSSA to report as required to the NASA Administrator at the monthly General Management Status Review (GMSR).

The CRAF/Cassini project will be required to respond to NASA Program Operations Plan (POP) Guidelines on a semi-annual basis. NASA management will conduct in-depth POP reviews with the JPL Project Office to address project status and detailed budget planning for all development years through launch. During these reviews, data for Headquarters monthly phased cost planning will be developed in the POP reviews, with variances reported monthly. If cost growth trends are reported for any mission element, the project has been directed to show offsets for the increase: (1) within the project budget; and, (2) without impacting mission requirements. If such offsets are ever exhausted, the descope plan will be implemented.

Status:

The Quarterly Project Reviews at JPL and monthly reviews by JPL and the OSSA Solar System Exploration Division management have been initiated. The first OSSA Major Flight Project/Program quarterly review for CRAF/Cassini was held in December 1989. The POP 90-1 Guidelines were issued to JPL for CRAF Cassini in February 1990. The first POP review for CRAF/Cassini will be conducted during this next reporting period.

VI) ACTION

Plan:

Implement, as necessary, program adjustments and/or descoping actions.

Status:

No actions necessary to date.

Enclosure 1

NON-RECURRING
COST CONTAINMENT
MILESTONES
(CRAF AND CASSINI)

	CRAF	CASSINI
Investigation Selection Complete	4Q86	4Q90
Non-Advocate Review (NAR)	2Q88	2Q88
Network Support Plan (NSP)	4Q89	4Q89
Flight Assignment Board (FAB)	4Q89	4Q89
Program Approval Document (PAD)	2Q90	2Q90
Project Plan	2Q90	2Q90
Support Instrumentation Requirements Documentation (SIRD)	3Q90	3Q90
Confirmation Reviews Complete	2Q91	1Q92
Descope Plan Complete	2Q91	1Q92
Spacecraft System PDR	4Q91	3Q92
Spacecraft System CDR	4Q92	3Q93
Mission Operations System (MOS) PDR	4Q92	NA
Mission Operations System (MOS) CDR	3Q93	2Q94

Enclosure 2

ANNUALIZED/TOTAL COST ESTIMATES

OFFICE OF SPACE SCIENCE AND APPLICATIONS
FY 1991 RECOMMENDED BUDGET

Comet Rendezvous Asteroid Flyby (CRAF)/Cassini Mission
(Dollars in Millions)

	FY 1990	FY 1991	FY 1992	FY 1993	FY 1994	FY 1995	BTC	TOTAL
CRAF & CASSINI MISSIONS	29.5	148.0	313.0	363.7	335.4	276.9	132.5	1,599.0
SPACECRAFT SYSTEMS	18.5	70.7	174.2	153.0	127.7	96.0	30.7	670.8
SCIENCE INVESTIGATIONS	7.7	41.7	90.8	100.9	64.6	44.8	9.8	360.3
RTG'S *	.5	17.4	32.0	30.9	17.6	5.8	1.7	105.9
OTHER	2.8	18.2	16.0	78.9	125.5	130.3	90.3	462.0
FY 1991 RECOMMENDED	29.5	148.0	313.0	363.7	335.4	276.9	132.5	1,599.0

* Funding requirements identified in August 17, 1989 meeting by CRAF/Cassini Project Manager and Deputy Assistant Secretary for Space and Defense Power Systems (DOE). (Current estimate amended to reflect subsequent discussion of February, 1990.)

Enclosure 3

COMET RENDEZVOUS ASTEROID FLYBY (CRAF) INVESTIGATION SELECTIONS AS OF 1986

CRAF SCIENCE INVESTIGATIONS AND AFFILIATIONS

Acronym	Investigation	PI/Team Leader	Prime/Sub Institutions
ISS	Imaging Science Subsystem	Dr Joseph Veverka	Cornell University
	(ISS hardware)		Jet Propulsion Laboratory
	(CCD detectors)		Ford Aerospace
VIMS	Visual/Infrared Mapping Spectrometer	Dr Thomas B. McCord	University of Hawaii
	(VIMS hardware)		Jet Propulsion Laboratory
TIREX	Thermal Infrared Radiometer Experiment	Dr Francisco P.J. Valero	NASA/Ames Research Center
	(TIREX hardware)		Santa Barbara Research Center
PENL	Penetrator/Lander	Dr William V. Boynton	University of Arizona
	(PENL hardware)		Ball Aerospace Systems Division
	(PENL science)		Lawrence Berkeley Laboratories
COMA	Cometary Matter Analyzer	Dr Jochen Kissel	Max Planck Institut fur Kernphysik
CIDEX	Comet Ice/Dust Experiment	Dr Glenn C. Carle	NASA/Ames Research Center
	(CIDEX hardware)		Martin Marietta Denver Aerospace
SEMPA	Scanning Electron Microscope and Particle Analyzer	Dr Arden L. Albee	California Institute of Technology
	(SEMPA hardware)		Jet Propulsion Laboratory
	(SEMPA detectors)		University of Southern California
CODEM	Comet Dust Environment Monitor	Dr W. Merle Alexander	Baylor University
	(CODEM hardware)		Martin Marietta Denver Aerospace
	(CODEM participation)		University of Kent (UK)
	(CODEM participation)		Rutherford Appleton Laboratories (UK)
NGIMS	Neutral Gas and Ion Mass Spectrometer	Dr Hasso B. Niemann	NASA/Goddard Space Flight Center
	(NGIMS calibration hardware)		University of Bonn
CRIMS	Comet Retarding Potential Analyzer	Dr Thomas E. Moore	NASA/Marshall Space Flight Center
	(CRIMS hardware)		University of Texas at Dallas
SPICE	Suprathermal Plasma Investigation of Cometary Environments	Dr James L. Burch	Southwest Research Institute
	(SPICE participation)		University College (UK)
MAG	Magnetometer	Dr Bruce Tsurutani	Jet Propulsion Laboratory
	(MAG electronics)		Technical University of Braunschweig
	(MAG sensors)		Imperial College (UK)
CREWE	Coordinated Radio, Electronics, and Waves Experiment	Dr Jack D. Scudder	NASA/Goddard Space Flight Center
	(CREWE hardware)		University of Minnesota
	(CREWE antennas & other hardware)		CNET/CRPE (France)
RSS	Radio Science Subsystem	Dr Donald K. Yeomans	Jet Propulsion Laboratory

NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546

Reply to Attn of: XC:HR:jl

MAY 7 1990

Honorable Robert A. Roe
Chairman
Committee on Science, Space
  and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed is a report requested by the Committee on Science, Space and Technology, U.S. House of Representatives, regarding NASA's decision not to accelerate the development of solar dynamic power for the Space Station Freedom. In Report 101-226 accompanying the FY 1990 NASA Authorization Bill, the Committee directed NASA to report on the technical, cost, and operating considerations that led to the decision.

Although solar dynamic power is clearly a promising technology for supplementing Space Station power requirements in the future, a review of the program cost, schedule and technical risk do not make acceleration a feasible alternative at the present time. The Space Station is, however, being designed to accommodate solar dynamic power modules in the future and development work on this technology will continue as an integral part of the Station design.

Sincerely,

Martin P. Kress

Martin P. Kress
Acting Assistant Administrator
 for Legislative Affairs

Enclosure

cc: Honorable Robert Walker

SPACE STATION SOLAR DYNAMIC POWER

Submitted to

COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

Office of Space Flight
National Aeronautics and Space Administration

March 1990

This report is submitted in response to a request by the Committee on Science, Space and Technology, U.S. House of Representatives. In Report No. 101-226 accompanying the FY 1990 NASA Authorization Bill, the Committee directed NASA to report on the technical, cost, and operational considerations that led to the decision not to accelerate the development of solar dynamic power.

SPACE STATION SOLAR DYNAMIC POWER

Table of Contents

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IV.	Technical and Operational Considerations	9
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I. OVERVIEW AND SUMMARY

NASA's approach to power generation on Space Station Freedom is to use photovoltaic arrays to meet the requirements of the baseline Space Station, then add solar dynamic power modules to provide additional capability as required to meet growth requirements. To implement this approach, procurement of four photovoltaic modules is now in progress. The baseline Space Station's electrical power system is being designed to accommodate solar dynamic power modules in the future. To that end, advanced development work on solar dynamic technology is ongoing.

In early 1989, NASA reviewed an option to adopt a hybrid power system for the baseline Space Station that would have used both photovoltaic and solar dynamic modules. This option would have required significant acceleration of the solar dynamic development effort to be concurrent with the photovoltaic procurement.

After reviewing this option's impact on program costs, schedule, and technical risk, NASA decided to adhere to its earlier plan to build an all photovoltaic system for the baseline Space Station, while continuing development of solar dynamic technology for future application.

The primary basis for this decision was the higher near-term cost of developing two different power generation systems simultaneously. Rapid acceleration of the solar dynamic technology development effort would have required additional early year funding at a time when the total annual program budget was being reduced. This would in turn have resulted in greater near-term funding reductions in other parts of the Space Station program.

Additionally, relying on solar dynamic power as part of the baseline Space Station development effort would have resulted in higher technical and schedule risks to the program, and the required increase in extravehicular assembly activity could not be supported when balanced against total program requirements at this stage of the program.

Although it is not incorporated into the baseline Space Station, solar dynamic power is clearly a promising technology for supplementing the baseline Space Station's capabilities in the future. As development of the Space Station continues, the budgetary, technical, and operational feasibility of early addition of solar dynamic power will continue to be examined.

II. DECISION BACKGROUND

In early 1986, the Space Station Freedom program selected a hybrid power system design that included both photovoltaic and solar dynamic power generation modules. The hybrid approach combined advantages of both technologies. For example, photovoltaic arrays are better suited for early deployment because of their greater ease of assembly, and because their less stringent pointing requirements offer greater system protection in contingency situations. Solar dynamic modules, in contrast, have some potential long-term cost advantages.

The hybrid approach was modified in early 1987 when the Space Station program was rephased. NASA determined that the baseline Space Station would have a 75 kW all photovoltaic power system, but at least 50 kW of solar dynamic power would be added when required in the future. This decision was primarily driven by the need to reduce initial program costs by avoiding simultaneous development of both power systems.

To implement this approach in the hardware development and fabrication stage of the baseline program, NASA began procurement of the 75 kW photovoltaic power system while ensuring that this system was designed to accommodate the addition of solar dynamic power modules in the future. NASA also initiated an on-going technology development and preliminary design effort for the solar dynamic system, and included an option for future procurement of a 50 kW solar dynamic system in the relevant work package prime contract. Programmatic and technical details of the solar dynamic development effort were described in "Solar Dynamic Power," a NASA report submitted to the Committee early last year.

In March 1989, a reassessment of the baseline Space Station's power system began as part of a program-wide technical audit conducted by the Space Station Program Office. The program conducted a three-month assessment of the option to accelerate solar dynamic power development for application in a hybrid power system for the baseline Space Station. Trade studies were conducted to weigh the advantages and disadvantages of the baselined approach against those of a hybrid photovoltaic/solar dynamic system for the baseline Station.

In June, NASA decided to stay with its earlier decision to build an all-photovoltaic power generation system for the baseline Space Station, while continuing preliminary design and technology development of solar dynamic power modules for addition at a later date.

III. COST CONSIDERATIONS

Near-Term Costs

The hybrid power system option considered assumed that half the photovoltaic power in the current Space Station 75 kW assembly sequence would be replaced by two solar dynamic modules with somewhat higher power generation capability (25 kW each).

Because of the relative immaturity of solar dynamics technology, there is a significant element of uncertainty in estimating development costs. The following summarizes estimates for solar dynamic development given the current state of design knowledge.

The estimated investment cost of the hybrid versus the baseline all photovoltaic system are compared in Figure 1. Although the cost data that comprise each approach have been refined since last year, the baseline all-photovoltaic system remains the most economic alternative in the near-term. Figure 1 indicates that the hybrid option would have increased program funding requirements by roughly $650 million over the next five years, and by roughly $700 million over the next decade. This includes the savings associated with building only two photovoltaic modules instead of four.

It should be noted that the decision not to accelerate solar dynamic power was made at a time when significant reductions in near-term program annual funding levels appeared likely. These reductions occurred when the final Space Station funding level for FY 1990 was determined, and they resulted in some adjustments to system designs, capability phasing, and the program schedule. If additional funding had to be diverted from other parts of the Space Station program to accelerate the solar dynamic development effort, the extent of program adjustments required would have been greater.

FIGURE 1
ESTIMATED COST IMPACT OF HYBRID POWER OPTION FOR BASELINE CONFIGURATION

FREEDOM

NET COST DIFFERENCES (MILLIONS OF RY DOLLARS)
(Additional requirements above current baseline)

	FY90	FY91	FY92	FY93	FY94	FY95	Balance to Complete	Total
Prime Contractor	8	51	90	96	98	82	45	470
Supporting Development	1	4	6	7	6	4	1	29
Lay-in Spares			34	42	57	45	5	183
Other Systems Impacts			2	3	3	3	2	13
Total Additional Requirement	9	55	132	148	164	134	53	695
Cumulative Total Additional Requirement	9	64	196	344	508	642	695	

Note: 1989 estimate assumes development start in FY90. Hybrid option assumes 3rd and 4th PV modules (18.75 kW each) are replaced by SD modules (25 kW each) at same point in assembly sequence, for total power level of 87.5 kW. Some adjustments to systems outside the power system work package would be required.

OSS-13012
4/24/90

Long-Term Operations Costs

A full and comprehensive assessment of long term operations costs was not possible in the time of the decision to stay with photovoltaic power. There was a significant degree of uncertainty associated with the operations cost estimates available because they were based on a wide range of assumptions, particularly regarding how often components would have to be replaced. The maturity of solar dynamics is significantly less than the photovoltaic system, so an allowance for optimistic assumptions must be made. However, it is anticipated that any operations costs for solar dynamics will be less than those for photovoltaic by some amount. Despite an assumed potential for lower operating costs for the hybrid system, NASA chose to stay with the all photovoltaic system in order to reduce near-term technical risk and to avoid significantly increasing the near-term development costs for the power system. NASA will continue to develop solar dynamic power concepts for power augmentation as the station evolves. During the Work Package 4 preliminary design review in July 1990, there will be an assessment of life cycle costs for the solar dynamic power system.

The elements of operations costs affected by the power system include propulsion fuel resupply requirements, logistics requirements associated with servicing needs and battery replacement, and long term cyclical replacement of the major elements, such as the photovoltaic arrays. The comparison between these costs is summarized below.

Fuel Supply. Station fuel resupply requirements for the hybrid system under consideration would have been lower than for an all photovoltaic system. A solar dynamic module would have a smaller cross-sectional area than its current photovoltaic equivalent, so the hybrid system would have lower atmospheric drag, and thus have lower Space Station reboost requirements.

Logistics. The hybrid system under consideration at the time would have had reduced logistics requirements associated with considerably fewer battery replacements and servicing needs. Unlike photovoltaic arrays, which must be complemented by stored power for when the station is in the Earth's shadow, solar dynamic systems store thermal energy to produce power during short periods of darkness.

Systems Replacement. Solar dynamic systems are expected to degrade in orbit more slowly than photovoltaic arrays, although environmental effects are not fully understood. Consequently, outyear logistics requirements for servicing and replacement would likely have been lower for the hybrid system than for the baseline all-photovoltaic system.

IV. TECHNICAL AND OPERATIONAL CONSIDERATIONS

The Space Station program examined a number of tradeoffs associated with adding solar dynamic power to the baseline program. Technical advantages include efficient power generation and energy storage, low drag, and compatibility with future power growth.

The technical disadvantages of solar dynamic power include a limited data base on the receiver assembly, the collector hardware, and the life of the phase change salt for thermal energy storage; the lack of any space-based experience with solar dynamic power; the need for a high degree of pointing accuracy; and a highly complex, extravehicular activity-intensive assembly process. Solar dynamic power also entails a higher schedule risk because of the immaturity of some of the technology.

While these concerns about solar dynamic power are being addressed in the development program and do not appear to preclude use of the technology at some time in the future,they would have made dependence early in the Space Station assembly sequence very risky. These issues are discussed below.

Assembly

If a hybrid system had been chosen, with solar dynamics as the primary power source for the station, the first time on-orbit assembly and operation of an entire solar dynamic module would occur would have been on the first or second assembly flight. Any problem with the module could delay station assembly. Adding this risk to the early stages of the assembly sequence was deemed unacceptable.

The assembly of the solar dynamic power module would require extensive extravehicular activity (EVA), with assembly of the concentrator being the most time-consuming. One estimate concluded that total EVA time for the entire assembly task for one module would be up to 18.25 EVA hours. This would consume the majority of the allocable EVA time per assembly flight. Studies are being done to see how this EVA time can be reduced, however. Although two solar dynamic modules could be brought up in the Shuttle at a time, only one could be assembled per assembly flight. The other would have to be stored on orbit until the next flight. In contrast, the photovoltaic modules can be assembled almost entirely without EVA.

Concentrator assembly in particular poses risk to overall Space Station assembly because the design is not yet sufficiently developed to assure that the mirror can be assembled easily on-orbit. To collect solar energy, the solar dynamic module uses a concentrating mirror (called the concentrator) to focus energy into a heat receiver which, in turn, transfers that energy to the thermodynamic power conversion equipment. The concentrator is approximately 60 feet in diameter and is made up of 19 hexagonal panels which are latched together. Each panel contains 24 triangular mirror facets which are approximately one meter per side. These facets are aligned and locked in the panels before launch. Latches which hold the panels together are also aligned before launch for on-orbit assembly by the Shuttle crew. The facets, panels and latches are being designed to assure that they will have no need for on-orbit adjustments. This approach has not yet been fully verified, but will be as part of Space Station advanced development activities. Maintenance of the on-orbit alignment will be demonstrated by ground-based testing, which is part of the planned solar dynamic development for Space Station Freedom.

Concentrator Pointing and Tracking

Solar dynamic power requires a high degree of concentrator pointing accuracy. If the module is too far out of alignment, it will cease generating power. Although the pointing requirement is less demanding than that of many communications satellites, it may be difficult to achieve if the concentrator surface is not sufficiently uniform or if problems arise with the concentrator pointing system. In contrast, photovoltaic systems are substantially more tolerant of pointing errors. The solar dynamic pointing system would function from the coarse pointing system established by the gimbals used to point the photovoltaic system. If this base were to become seriously impaired, the solar dynamic pointing controls would be driven to their limit and power generation would be lost. Operational procedures for the Space Station such as Shuttle docking and station reboost maneuvers will need to be tailored to, and coordinated with, the power generating system.

Effects of Space Environment

Because solar dynamic power has not yet been tested in space, little is known about the space environment's effects on the lifetime of solar dynamic hardware. For example, the effects of atomic oxygen on the concentrator surface are unknown. Also, meteroid and orbital debris damage would likely affect concentrator life and maintenance, although this damage should be less than that for photovoltaic arrays because the concentrator is a passive surface containing no circuits or active energy converters.

Another unknown relates to the effects of microgravity on the salt mixture in the solar dynamic power module's receiver. The energy storage material, LiF/CaF2 euctectic salt, undergoes a volume decrease of 15 percent upon freezing. This salt is contained in a canister inside the receiver. The reduction of the salt's volume when frozen (creating a void) has led to questions about the canister's thermal performance, and the impact on the containment canister arising from the expansion of the salt upon subsequent remelting. The canister is being designed to accommodate the presence of the salt void and is being tested. Physical properties of the salt container metal and its durability over time are being determined. However, no long term destructive testing on the canister has been done yet. These issues are being addressed in the solar dynamic supporting development activities.

System Design Complexities

Both the solar dynamic and the photovoltaic power systems require complex voltage, energy storage and thermal controls. The solar dynamic module has an additional requirement for careful matching of solar input, thermal energy storage, and engine loads. While this is not a major concern, it should be noted that both systems, and the solar dynamic system in particular, are complex in nature. However, because of NASA's extensive experience with photovoltaics, there is on average, less development risk with its development compared to the solar dynamic system.

V. CONCLUSIONS

Three key factors outweighed the potential life cycle cost advantages of solar dynamic power in the recent decision not to accelerate its development into the baseline Space Station configuration.

First, near term annual funding requirements would be too high. Accelerating the availability of solar dynamic power would require its full scale development in parallel with the necessary photovoltaic power capability. Additional funding for parallel development is not available -- in fact, near-term funding expectations have been reduced. Consequently, this option could not be implemented without excessively burdening other areas of the Space Station program.

Second, bringing solar dynamic power into the baseline configuration would put this development effort in the Space Station program's critical path, and would result in a high degree of cost, schedule, and technical risk. In contrast, there is less uncertainty associated with developing the photovoltaic modules alone, so costs and schedule risks are much lower.

Third, assembling solar dynamic modules on-orbit is operationally more complex than assembling photovoltaic modules. In particular, the extravehicular activity requirements for assembly are incompatible with total EVA availability and other program EVA requirements in the early stages of Space Station operations. Addition of solar dynamic modules at some time in the future after the first four photovoltaic modules are in place is operationally more feasible.

Although a hybrid power system was not selected for the baseline Space Station configuration, solar dynamic power is clearly a promising technology for supplementing the Space Station's baseline capabilities in the future. Because of the potential life cycle cost advantages of this technology, NASA plans for expanding the Space Station's capabilities assume that growth power requirements will be met by the addition of solar dynamic power modules.

Consequently, NASA will continue its preliminary design and technology development efforts on the solar dynamic modules, and will also continue to examine the budgetary, technical, and operational feasibility of early addition of these as development of the baseline Space Station progresses.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

4 1990

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed, for your information, is a copy of the letter to the Speaker of the House of Representatives transmitting the Semiannual Report of the Inspector General of NASA for the period ending March 31, 1990, the Inspector General Report, and the NASA Management Report on the Status of Audit Followup.

Sincerely,

Richard H. Truly
Administrator

Enclosures

cc:
Honorable Robert Walker

NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546
Office of the Administrator

JUN 4 1990

Honorable Thomas S. Foley
Speaker of the House of Representatives
Washington, DC 20515

Dear Mr. Speaker:

Pursuant to the provisions of the Inspector General Act of 1978 (Public Law 95-452) and the Inspector General Act Amendments of 1988 (Public Law 100-504), I am providing the enclosed Semiannual Report of the Inspector General and the Semiannual NASA Management Report on the Status of Audit Followup. The latter report includes the status of followup on audits of NASA programs and operations conducted by or for the NASA Office of Inspector General, the General Accounting Office, and audits of contractors conducted on behalf of NASA by the Defense Contract Audit Agency.

The reports address potential monetary savings, rather than assured savings. I would like to stress this point because, in many cases, NASA management has not as yet concurred with or been able to verify the savings identified in the audit reports. All reported potential savings will, however, receive significant management attention to assure their recovery or better use.

We recognize the audit followup process as a valuable management tool and, although further enhancements are required, the reports do reflect significant progress in this area.

Sincerely,

Richard H. Truly
Administrator

2 Enclosures

NASA

SEMIANNUAL
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANAGEMENT REPORT
ON THE
STATUS OF AUDIT FOLLOWUP

as of

March 31, 1990

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Management Report on Semiannual Audit Followup Status (Noncontract) for Six Month Period Ending March 31, 1990				
	I. OPEN - BEGINNING OF PERIOD	*II. NEW - REPORTS REC'D DURING PERIOD*	*III. FINAL ACTIONS DURING PERIOD*	*IV. OPEN - END OF PERIOD*
A. No. of Audit Reports	38	25	(SEE PAGE 2)	44
B. No. of Recommendations (Monetary)	15	14		20
1. No. of Management Decisions	11	6		8
(a) Disallowed Costs	$9,842,285	0		$8,887,275
(b) Funds Put to Better Use	$43,460,000	$30,249,000		$42,493,100
2. No. of Pending Management Decisions	4	8		12
(a) Disallowed Costs (AE) *	$3,900,000	$772,000		$4,672,000
(b) Funds Put to Better Use (AE)	$33,390,000	$27,903,000		$30,077,100
C. No. of Recommendations (Nonmonetary)	145	113		126
1. No. of Management Decisions	143	111		123
2. No. Pending Management Decisions	2	2		3
D. Total No. of Recommendations	160	127		146
				131
1. No. of Management Decisions	154	118		15
2. No. Pending Management Decisions	6	9		2

III. FINAL ACTIONS DURING PERIOD	
A. No. of Audits Reports	19
B. No. of Recommendations (Monetary)	9
C. Disallowed Costs Recoveries	$955,510
1. Collections and Offsets	$955,510
2. Property	0
3. Other	0
D. Write–offs	$6,321
E. Total of C and D	$961,831
F. Funds Put to Better Use	$31,215,900
1. Value of Recommendations Implemented (Completed)	$10,715,900
2. Value of Recommendations that Management concluded should not or could not be implemented.	$20,500,000
G. No. of Recommendations (Nonmonetary)	132
H. Total No. of Recommendations	141

* AE – Auditor Estimate

V. PRE-MARCH 31, 1989 AUDITS PENDING FINAL ACTION (OPEN OVER 1 YR)

AUDIT #	*AUDIT TITLE*	*DATE*	*RECOMMEND # NON*	*# MON*	*D.C. **	*B.U.F. **
A-JS-87-005	SPACE TRANSPORTATION SYSTEM OPERATIONS CONTRACT Comments: Management reports contract modification and recovery of appropriate incentive fees have been documented. Verification is pending an OIG audit of renegotiation of incentive fees.	3/88		1		$2,800,000
A-JS-87-009	CONTRACTOR FACILITY ACQUISITIONS Comments: Pending results of DCAA audit of overhead rates.	3/88		4		$37,197,000
A-HQ-88-001	PCIE COMPUTER INTEGRITY TASK 2A Comments: Remaining action is to conduct assessment of sensitive or valuable applications and resources.	7/88	2			
A-HQ-87-001	SPACE STATION RELOCATION Comments: NASA to assume JPL lease. Yet to resolve: HQ coordination of specific facility requirements.	9/88	2			
A-JS-87-004	SUBCONTRACT MANAGEMENT Comments: OIG recommends collection of $6.9 million excessive profits on Rockwell's subcontractors.	9/88		1	$6,900,000	
A-MA-87-006	SUBCONTRACT MANAGEMENT Comments: Awaiting DCAA audit reports concerning refunds or price adjustments from prime contractors.	11/88		1	$572,950	
A-KE-87-003	ADP MAINTENANCE Comments: KSC submitted a revised plan to the OIG to coordinate maintenance and repair of contractor PCs and software problems.	12/88	3			
A-JP-88-002	STAFFING LEVELS Comments: Pending OIG concurrence to close actions taken to monitor progress in implementing corrective actions. Number of technical support contractors continues to decline.	3/89		1	$11,500,000	
A-KE-88-003	MAXIMUM WORKTIME PRACTICES Comments: KSC reviewing an EG&G study for an automated worktime tracking system.	3/89	1			

* D.C. = Disallowed Costs, B.U.F. = Better Use of Funds, N-MON = Nonmonetary Recommendations,
MON = Monetary Recommendations

REPORT PERIOD: APRIL 1 1989 - SEPTEMBER 30 1989

	Audit Rpt. No.	Rpt. Date	Contractor Name	*Audit Type	Cost Avoidance	In Litigation	Resolved or Unresolved	Resolution Target Date	Disposition Target Date	Comments
I. OPEN REPORTS	7141-8E160914	09-30-88	E. B. White	B	17,785		U	12-90	12-90	Same as above.
	3521-8E160016	09-30-88	Northrop Svcs Inc	B	492,161		U	06-90	06-90	DCAA to provide calculation of questioned costs allocable to contract by 5-1-90. Contractor has concurred with most audit findings. Form 456 will be issued.
	2180-8B420002-0454	10-03-88	Northrop Corp.	B	329,057		U	05-90	05-90	ACO currently negotiating with Rockwell (prime). Decision expected by 4-30-90.
	1231-8L240018	10-14-88	Lockheed Space Opns Co.	A	N/A		U	09-90	09-90	Written response received from Contractor. ACO reviewing. Final determination pending.
	7121-8F160001	11-03-88	Johnson Eng Corp	C	N/A		U	04-90	04-90	PCO holding fee vouchers as of 1/89. Ctr has revised timekeeping procedures. Follow-up audit to be conducted.
	1231-8RL44100010	11-09-88	Lockheed Space Opns Co.	E	N/A		U	06-90	06-90	Awaiting revised disclosure statement from Contractor. Should receive by 5-31-90. ACO will review and make determination of adequacy.
	1231-8RL44200046	01-30-89	Lockheed Space Opns Co.	E	1,208,677		U	12-90	12-90	Additional information received from DCAA on 3-30-90. ACO currently reviewing information.
	7611-9J172001	03-21-89	Industrial Contractors	E	701,409		U	08-90	08-90	Government made offer for settlement. Contractor reviewing offer.
B. Reports 6-12 months old	1231-9R044200022	07-19-89	Boeing Aero Oper Inc.	E	N/A		U	12-90	12-90	Contractor rebuttal to initial determination received 2-12-90. ACO reviewing submittal.
	1231-9R044200027	08-24-89	Boeing Aero Oper Inc.	E	N/A		U	12-90	12-90	Cost impact proposal due from Contractor on 4-27-90.
	4461-9B160.005	08-31-89	MDAC - Huntsville	B	0		U	07-90	07-90	ACO negotiating settlement.
	4461-9F160002	08-31-89	McDonnell Douglas - ES	B	0		U	06-90	06-90	Awaiting DCAA assist audit. Discussed with DCAA auditor 3/90. Estimate receipt 5/90.
	1231-9RL44200035	09-25-89	Lockheed Space Operations	E	N/A		U	09-90	09-90	DCAA reviewing contractor response to audit findings (received 12/89).
	1231-9RL24030032	09-19-89	Lockheed Space Operations	A	N/A		U	09-90	09-90	Written response to audit findings received from Contractor. ACO determination pending.
	1601-9K160023	09-26-89	Analex Corporation	B	110,995		U	04-90	04-90	Contractor response to audit findings received 1/90. Currently under review.
	1231-9RL24030036	09-26-89	Lockheed Space Operations	A	N/A		U	09-90	09-90	Contractor response to audit findings received. ACO final determination pending.
	1601-9K160009	09-29-89	Analex Corporation	B	1,454,145		U	04-90	04-90	Contractor response to audit findings received 1/90. Currently under review.
	1601-9K160008	09-29-89	Analex Corporation	B	476,300		U	04-90	04-90	Contractor response to audit findings received 1/90. Currently under review.
	1231-9RL16240014	09-29-89	Lockheed Space Operations	B	769,223		U	09-90	09-90	Additional information from DCAA received 3/90. ACO reviewing information.
	1231-9BG10523054	09-29-89	EG&G Florida, Inc.	F	239,902		U	09-90	09-90	Awaiting Contractor's response.
C. Reports < 6 months old	4461-9E160021	11-02-89	McDonnell Douglas	B	333,066		U	08-90	08-90	Awaiting Contractor's response.
	4461-9E160052	12-07-89	McDonnell Douglas	B	365,264		U	08-90	08-90	Awaiting Contractor's response.
	4461-9C160.001	12-12-89	MDAC - Huntsville	B	1,349,971		U	07-90	07-90	ACO negotiating settlement.
	0501-9A420003	01-31-90	G.E. Astro Space	B	85,968		U	05-90	05-90	Contractor response received 3/90. Negotiations scheduled 5/90.

* See Legend

REPORT PERIOD: APRIL 1 1989 - SEPTEMBER 30 1989

1. OPEN REPORTS

A. Overaged Reports (> 12 months old)

Audit Rpt. No.	Rpt. Date	Contractor Name	* Audit Type	Cost Avoidance	In Litigation	Resolved or Unresolved	Resolution Target Date	Disposition Target Date	Comments
1231-5L140017	10-31-85	Lockheed Space Opns	B	244,888		U	12-91	12-91	Awaiting settlement of corporate rates.
1231-5L160058	02-28-86	Grumman Tech Svcs	E	71,386		U	12-91	12-91	Awaiting settlement of corporate rates.
1231-5L140038	04-25-86	Lockheed Space Opns	B	597,396		U	09-91	09-91	Awaiting settlement of corporate rates.
1211-6C160003	08-25-86	Sverdrup Tech	G	1,797,569		U	05-90		ACO negotiating with contractor.
7261-5P160043	05-11-87	Umpqua Research Company	G	34,201		04-09-90		06-90	Negotiation conducted 3/90. Final price negotiated. Amount sustained $4,316. Processing final voucher.
7261-5P160045	05-11-87	Umpqua Research Company	G	13,666		04-09-90		06-90	Negotiation conducted 3/90. Final price negotiated. Amount sustained $8,166. Processing final voucher.
7261-5P160065	05-11-87	Umpqua Research Company	G	1,327		04-09-90		06-90	Subsequent closing audit accepted contractor's claimed costs. Final price negotiated. Processing final voucher.
1231-7B441062	05-12-87	Boeing Tech Opns	E	N/A		U	12-90	12-90	Revised cost impact proposal due 4-27-90.
1231-7G420011	06-26-87	EG & G Florida, Inc.	D	841,612		U	05-90	05-90	C.O. scheduled to meet with Contractor to discuss new NASA position by 4-30-90.
6501-8D420004	01-13-88	RCA Corp.	D	452,429		U	05-90	05-90	NASA OIG and Justice Dept. not to pursue criminal charges. No evidence of fraud found (memo. 9/89). Contractor response received 2/90. Negotiations set for 4/23/90.
1231-8L445037	01-28-88	Lockheed Space Opns	E	344,219		U	07-90	07-90	ACO researching legal issue on cost impact of implementation.
1231-8H172004	02-29-88	W & J Construction Corp.	E	347,545	X	U			Claim N86-85C filed in U.S. claims court. In discovery stage since 09-89. Trial could begin by end of CY 1990.
1231-8D442037	03-03-88	McDonnell Douglas Space Sys	A	N/A		U	12-90	12-90	DCAA to determine whether corporate problem; may change level of parties. DCAA surveying field offices to determine extent of problem. Awaiting results of survey.
2191-8E177424	05-27-88	Fokker Space & Sys B.V.	B	N/A		U	10-92	12-92	Prime will request updated report prior to start of 09-92 negotiations.
2191-8X240636	05-27-88	Fokker Space & Sys B.V.	A	N/A		U	10-92	12-92	Prime will request updated report prior to start of 09-92 negotiations.
1231-8U442048	06-01-88	USBI Co.	E	N/A		U	05-90	05-90	Contractor submitted cost impact proposal. DCAA report due 4-30-90.
3521-8E442129	06-30-88	Rockwell International	E	53,314		U	05-90	05-90	Written response from Contractor due 4/90. ACO to make determination based on response.
1231-7A240026	08-19-88	Grumman Tech Svcs	A	N/A		U	09-90	09-90	Awaiting DCAA follow-up report on subcontractors corrective actions.
1231-8D240025	09-29-88	McDonnell Douglas Space Sys	A	N/A		U	05-90	05-90	Contractor response to DCAA follow-up review (received 10/89) determined inadequate. Requested corrective action 2/90.
7161-8E160917	09-30-88	E. B. White	G	14,662		U	12-90	12 90	NASA OIG informed C.O. 1/90 of investigation of Contractor. Advised not to finalize rates until investigation complete.
7161-8E160917	09-30-88	E. B. White	G	32,179		U	12-90	12-90	Same as above.
7161-8E160915	09-30-88	E. B. White	G	35,103		U	12-90	12-90	Same as above.
7161-8E160919	09-30-88	E. B. White	G	10,398		U	12-90	12-90	Same as above.
7161-8E160919	09-30-88	E. B. White	G	19,409		U	12-90	12-90	Same as above.
7161-8E160918	09-30-88	E. B. White	G	27,583		U	12-90	12-90	Same as above.
7161-8E160918	09-30-88	E. B. White	G	46,356		U	12-90	12-90	Same as above.
7161-8E160916	09-30-88	E. B. White	G	44,459		U	12-90	12-90	Same as above.

*See Legend

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REPORT PERIOD: APRIL 1 1990 - SEPTEMBER 30 1990

I. OPEN REPORTS
                                                                 *  Audit    Cost         In      Resolved or   Resolution  Disposition
      Audit Rpt. No.     Rpt. Date      Contractor Name              Type  Avoidance  Litigation  Unresolved    Target Date Target Date                 Comments
    ------------------   --------  ------------------------          ----  ---------  ----------  -----------   ----------- ----------- ----------------------------------------------------------------------
    [illegible]          08-01-90 Sverdrup Tech.                      B      N/A                       U           09-90       09-90    ACO reviewing.
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Legend: Audit Type Codes

Code	Type of Audit
A	Estimating Systems Survey
B	Accounting System Review
C*	Internal Control Review
D	Defective Pricing Review
E	Cost Accounting Standards
F*	Operations Audit
G*	Incurred Costs
H*	Settlement of Final Indirect
I*	Final Pricing
J*	Terminations
K*	Equitable Adjustment Claims
L*	Hardship Claims
M*	Escalation Claims

* Reported costs or rates questioned and/or qualified must equal $100,000 or more.

II. REPORTS CLOSED

	Audit Rpt. No.	Rpt. Date	Contractor Name	Audit Type	Date of Deposition	Cost Questioned or Cost Avoidance	Costs Sustained/ Avoided
A. Reports listed as overage prior report.	7221-2C160838-001	06-22-83	Techn Dev of Cal, Inc.	H	01-19-90	233,597	233,597
	7231-6A420004	05-06-86	Morton Thiokol	D	07-03-89	5,168,575	600,000
	1231-8A442052	03-10-88	Grumman Tech Serv Inc	E	12-05-89	36,516	25,126
	3521-8D240106	09-19-88	Astro International Corp.	A	08-10-89	N/A	N/A
B. Other reports closed during period.	1231-5L159021	11-09-88	Lockheed Space Opns Co.	G	12-22-89	927,930	471,955
	1231-89G13030021	02-07-89	EG&G Florida Inc	C	03-15-89	N/A	N/A
	7221-89E17700003	04-28-89	Psycho-Linguistic Research	B	12-08-89	N/A	N/A
	6291-89F24020002225	05-04-89	APD Cryogenics, Inc	A	12-04-89	0	0
	1231-89G11010028	06-02-89	EG&G, Florida, Inc	C/F	02-21-90	N/A	N/A
	4461-9G442003	06-15-89	McDonnell Douglas Astro Co	E	12-27-90	N/A	N/A
	1231-88L14300028	08-21-89	Lockheed Space Operations	G	12-22-89	102,057	81,815
	1231-89L11980031	09-05-89	Lockheed Space Operations	G	09-05-90	114,255	114,255
	1231-89L14300015	09-29-89	Lockheed Space Operations	G	12-22-89	181,676	184,841
	1681-0K240002	01-24-90	W. L. Tanksley	A	01-24-90	N/A	N/A

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

General Accounting Office Audits

	TOTAL	*COMMENTS*
BEGINNING		Not Applicable
Audits Open	3	
No. Recom.	14	
NEW		
Audits Recd	2	
No. Recom.	3	
CLOSED		
No. Audits	2	
No. Recom.	4	
ENDING BAL		
Audits Open	3	
No. Recom.	13	

SPACE STATION FREEDOM
CAPITAL DEVELOPMENT PLAN
FISCAL YEAR 1991

Submitted to the

Committee on Science, Space and Technology
U.S. House of Representatives

and the

Committee on Commerce, Science and Transportation
U.S. Senate

Office of Space Station
National Aeronautics and Space Administration

April 1990

The "Capital Development Plan - FY 1991" is submitted to Congress as directed in the Fiscal Year 1988 NASA Authorization Act (P.L. 100-147). Section 107 of the Act directs NASA:

> "For each of the fiscal years 1989 through 1996, the Administrator, along with the President's submission to the Congress of the annual budget request for the National Aeronautics and Space Administration, shall submit a capital development plan for the space station program. Each plan shall include the estimated cost of all direct research and development; space flight, control and data communications; construction of facilities; and the research and program management for the fiscal year involved and the two succeeding fiscal years."

This report provides an update on the current status of the program (relative to the description in last year's Capital Development Plan), and includes updated projections of capital costs associated with the Space Station development effort.

SPACE STATION CAPITAL DEVELOPMENT PLAN - FY 1991

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List of Acronyms

I. INTRODUCTION AND SUMMARY

The Space Station Freedom program is one year closer to the First Element Launch milestone than it was when the FY 1990 Capital Development Plan was prepared. During the last year, considerable progress was made across all areas of the program, and design activities are accelerating in preparation for the series of preliminary design reviews planned for 1990.

Some adjustments have been made in the program during the last year, primarily in response to reductions in the FY 1990 budget and anticipated funding levels for the next few years. Although First Element Launch is still scheduled for FY 1995, outyear assembly milestones have been delayed up to a year and a half. Some changes to system designs have been made to reduce near-term costs and/or development risks. User capabilities of the baseline Space Station at the Assembly Complete milestone are essentially unchanged, although some adjustments have been made to target dates in the assembly sequence when certain capabilities are available. The Polar Platform development effort has been transferred from the Space Station program to the Office of Space Science and Applications.

The required Space Station funding profile has also been adjusted. To maintain the current program schedule and content, the program requires $2.451 billion for FY 1991, $2.907 billion for FY 1992, and $3.031 billion for FY 1993. These funding levels are lower than projected last year because the program changes described above resulted in the deferral of some costs to later in the development program. The estimate of total development costs through the Assembly Complete milestone is still within the $13 billion (in FY 1984 constant dollars) proposed cap.

II. SPACE STATION PROGRAM STATUS

During FY 1989, NASA undertook a major review of the Space Station Freedom program's configuration, management, budget and schedule. The review was motivated by a number of factors. First, the new program managers, who had arrived in June, wished to reassess the level of program risk in order to see where it could be reduced. Second, the program was in a transition period from preliminary definition to preliminary design, requiring possible changes in program organization and management practice. Third, there were a number of indications that the Space Station would not receive the appropriation it had requested, motivating a cost assessment to see where the possible reduction could be taken with the least impact to Station capabilities.

The review included the development of a set of programmatic and system-level options, which were then iteratively assessed by Space Station management, NASA's international partners, space station users, and NASA officials outside the Space Station program. The goal was to better balance program content, cost, schedule and technical risk in the program. Many of the initial options considered were discarded as being too harmful to user capabilities or the interests of the international partners. The review resulted in the deletion of only a very few station capabilities, although the availability of many had to be rescheduled in order to reduce funding requirements and program risk. Specific changes to the configuration are listed below.

The review placed high priority on holding early program milestones in order to assure progress on hardware development. First element launch was held to its target date of early 1995. Delay of other major program milestones was held to a minimum. The Space Station Preliminary Design Review, a key step in definitizing station subsystem and system design, will be carried out in late 1990.

Changes in Space Station Systems and Subsystems

Since last year's Capital Development Plan was submitted, design changes have been made in several systems and subsystems to reduce near-term costs and/or technical risk. The impacts of these changes are reflected in current cost estimates. Major system design changes and related programmatic changes are shown below.

- The primary power distribution system has been changed to a 160 volt direct current system from the 440 volt alternating current system that had been planned.
- The existing Space Shuttle space suit will continue to be used after PMC instead of the previously planned new space suit. (However, studies of suit technologies and potential requirements will be conducted in FY 1991 under the advanced programs/exploration initiative element.)

- A hydrazine propulsion system will be used instead of the previously planned hydrogen/oxygen system. (Studies of advanced propulsion systems, including hydrogen/oxygen, will be studied in FY 1991 within the advanced programs/exploration initiative element of the budget.)
- One airlock will be built instead of two (under review).
- External payloads will be cooled passively instead of actively.
- Lab support equipment has been removed as a baseline funding requirement within the Space Station development budget (NASA has not yet determined whether this would best be funded within the Space Station development program or by the Office of Space Science and Applications). These requirements are being reviewed jointly with OSSA, and funding and management responsibility will be agreed upon after completion of the review.
- Management of the Polar Platform has been transferred to the Office of Space Science and Applications, and the requirement for Polar Platform hardware commonality with the manned base has been deleted.
- The solar dynamic power generation system ground test has been deferred indefinitely. Preliminary design of a solar dynamics module will continue in the development program, and further assessments of solar dynamics power and an associated hybrid power distribution system will be conducted in FY 1991 under the advanced programs/exploration initiative element of the budget.

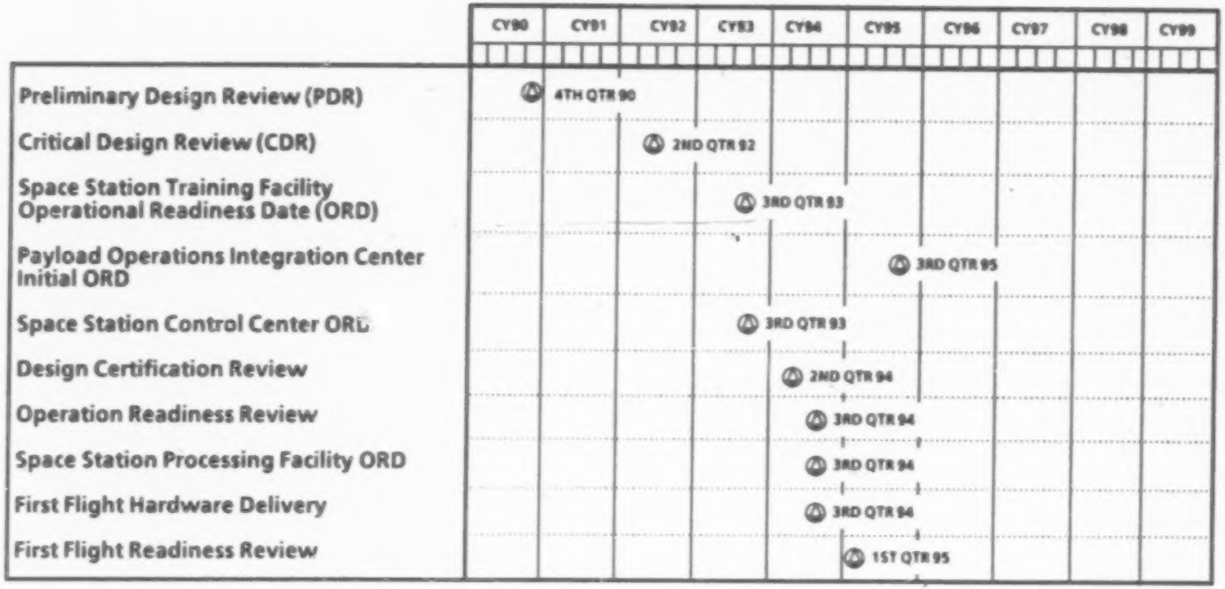
Program Schedule and Major Milestones

Figures 1a and 1b show the major Space Station schedule milestones. The recent program adjustments discussed above have resulted in adjustments to some of the dates for these milestones since the submission of the FY 1990 Capital Development Plan.

The Space Station preliminary design review (PDR) has been shifted from the third quarter of 1990 to the fourth quarter of that year. In addition, the operational readiness date for the Space Station Training Facility was slipped from the first to the third quarter of 1993 and the Space Station Control Center (SSCC) was advanced from March 1994 to September 1993. The Payload Operations Integration Center initial operational readiness date also shifted from the fourth quarter of 1993 to the third quarter of 1995.

The First Element Launch (FEL) is still planned for the first quarter of 1995. It will include initial components of the

Figure 1a:
SPACE STATION PROGRAM MILESTONES (PRE-ASSEMBLY)



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(1 of 2)
4/6/90

Figure 1b:
SPACE STATION PROGRAM MILESTONES (ASSEMBLY)

	CY90	CY91	CY92	CY93	CY94	CY95	CY96	CY97	CY98	CY99
First Element Launch (FEL)						1ST QTR 95				
Man-tended Capability (MTC)							2ND QTR 96			
Permanently Manned Capability (PMC)								3RD QTR 97		
Japanese Module launch									1ST QTR 98	
European Space Agency Module launch									2ND QTR 98	
Assembly Complete Phase 1										3RD QTR 99

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3/1/90

manned base as well as the Flight Telerobotic Servicer (FTS). Man-Tended Capability (MTC), established with the launch of the U.S. laboratory, has been shifted from the fourth quarter of 1995 to the second quarter of 1996. Permanently Manned Capability (PMC) has shifted from the fourth quarter of 1996 to the third quarter of 1997. Finally, the Phase 1 Assembly Complete (AC) milestone has been shifted from the first quarter of 1998 to the third quarter of 1999.

The Japanese laboratory module launch changed from the second quarter of 1997 to the first quarter of 1998. The European Space Agency laboratory module launch has shifted from the third quarter of 1997 to the second quarter of 1998. Responsibility for the U.S. Polar Platform will transfer to the Office of Space Science and Applications in FY 1991, so it is no longer shown on this schedule.

III. TOTAL SPACE STATION DEVELOPMENT COSTS

A. Background

This section provides an updated projection of funding requirements through FY 1993. These estimates include both costs directly incurred in the Space Station development program and associated capital costs incurred by other NASA program offices. These costs are divided into four major categories:

- **Research and Development** (R&D) provides for activities required to develop the Space Station itself, and also to develop space transportation capabilities required for its assembly and operation
- **Space Flight, Control and Data Communications** (SFCDC) provides for activities associated with transportation operations required for Station assembly, and tracking and data acquisition capability development
- **Construction of Facilities** (CoF) provides for building, expanding, and modifying facilities necessary for Station development and operations
- **Research and Program Management** (R&PM) provides funding for NASA civil service personnel and associated administrative tasks supporting Space Station R&D and operations.

Figure 2 shows cost estimates for the budget line items in these accounts that are capital costs related to building the Space Station. Each of these line items is described below. Estimates for FY 1990 and 1991 are consistent with the total FY 1990 appropriation and the FY 1991 budget request respectively. Outyear projections do not include provision for program scope beyond that already approved. Projected costs for Space Station operations, which are not part of program capital costs, are shown parenthetically at the bottom of Figure 2 for informational purposes only.

B. Space Station Development

This line of the R&D account applies to definition and design/development of the baseline Station, development of the FTS, advanced programs, and some concept definition work on an assured crew return capability (prior to FY 1988). Each of these areas is a separate component of the Space Station development line. Development of scientific payloads for the Space Station is covered elsewhere in the NASA budget.

Funding for the Space Station definition effort was concluded in FY 1987. Design/development costs shown in Figure 2

SPACE STATION FREEDOM PROGRAM
CAPITAL DEVELOPMENT PLAN
PRELIMINARY FY 91 BUDGET ESTIMATES

	FY 87	FY 88	FY 89	FY 90	FY 91	FY 92	FY 93	FY 87-93 TOTAL
RESEARCH AND DEVELOPMENT	420	399	912	1757	2506	2762	2657	11413
SPACE STATION	420	392	900	1750	2442	2696	2581	11181
DEFINITION	250	--	--	--	--	--	--	250
DEVELOPMENT	147	367	842	1661	2300	2569	2489	10375
FTS	20	21	46	80	106	107	72	452
ADV PROGRAMS	--	4	12	9	36	20	20	101
ORBITAL DEBRIS RADAR	--	--	--	--	--	--	--	0
ACRC	3	--	--	--	--	--	--	3
SPACE TRANS CAP DEV	--	7	12	7	64	66	76	232
SPACEFLIGHT, CONTROL, AND DATA COMMUNICATIONS	3	5	10	5	4	19	62	108
SPACE TRANS OPS	--	--	--	--	--	--	18	18
SPACE & GROUND NETWORK, COMM & DATA SYSTEMS	3	5	10	5	4	19	44	90
CONSTRUCTION OF FACILITIES	18	2	2	55	44	73	79	273
RESEARCH AND PROGRAM MGMT	80	83	98	128	156	156	156	857
TOTAL SPACE STATION	521	489	1022	1945	2710	3010	2954	12651
(NON-ADD SPACE STATION OPS)		(--)	(--)	(--)	(9)	(70)	(163)	(242)

Note: FY87 through FY90 in RY$; FY91 and beyond in FY91$

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include funding for design, fabrication, and testing of integrated systems and elements. Polar Platform development activities are included only through the end of FY 1990, since the management of that project has been transferred outside the Space Station program beginning in FY 1991. Future Capital Development Plans will not include Polar Platform in their discussion of development costs. Advanced programs covers planning necessary to make the baseline Space Station design flexible enough to easily accommodate future technologies and missions, advanced development work to mature new enabling technologies, and support for commercial participation. In FY 1991 only, $20 million of the $36 million budget for advanced programs will be applied toward studies and preliminary design of technologies which may be required to support the exploration initiative. Initial concept definition of an assured crew return capability was once part of the Space Station program, but was transferred to the Space Transportation Capability Development line of the R&D account in 1988.

C. Space Transportation Capability Development

This line of the R&D account applies to assessment and development of transportation options for the Space Station and to development of new capabilities required for its assembly and operations. Specific activities include upgrading the Shuttle's remote manipulator system, developing a Space Station docking adapter for the Shuttle, and continuing definition of an assured crew return capability for the Station.

D. Space Transportation Operations

The transportation costs for Station assembly are included in this line of the Spaceflight Control and Data Communications (SFCDC) account. No funding is included in this line until FY 1993; the $18 million in FY 1993 is that year's portion of the marginal cost of the three Space Shuttle flights in FY 1995 required for Space Station assembly.

E. Space and Ground Network, Communications and Data

This line of the SFCDC account applies to development of tracking and data acquisition capabilities required for Space Station operations by the NASA Office of Space Operations. Funding in this line covers Space Station elements of the Customer Data Operations System, which will provide data capture, data processing, and polar platform control. This system will also provide tracking, data acquisition, and communications through the Tracking and Data Relay Satellite System. The estimates for the unique support of the Space Station Freedom requirements reflect the transfer of the Polar Platform to the Earth Observing System after 1990.

F. Construction of Facilities

The CoF line applies to construction activities of ground facilities needed for the Space Station program. These activities are primarily focused on development testing, pre-launch processing, logistics, training and simulations, human performance tests, and orbital debris characterization. The program has relatively modest CoF requirements considering its size and duration due to the extensive use of existing facilities for Space Station development and operations.

G. Research and Program Management

The R&PM line applies to the direct salaries and benefits for civil service personnel currently supporting the Space Station Freedom program. This includes personnel at the work package centers, the research centers, the Space Station Freedom Program Office, and NASA Headquarters.

H. Changes from FY 1990 Capital Development Plan

The funding estimates in this year's Capital Development Plan for FY 1987-1993 total $12.651 billion, without provision for inflation beyond FY 1991. This is a net reduction of $1.372 billion from the funding estimates in the FY 1990 Capital Development Plan (see note 1). By fund source, this includes reductions in Research and Development (-$1.366 billion) and Spaceflight, Control, and Data Communications (-172 million). These reductions are partially offset by increases in Construction of Facilities (+$111 million) and Research and Program Management (+$55 million). The following paragraphs discuss these changes by fund source.

1. Research and Development

The $1.366 billion reduction in Research and Development represents a reduction in Space Station of $1.423 billion offset by an increase of $57 million in Space Transportation Capability Development.

In Space Station, Development was reduced by $1.671 billion, Flight Telerobotic Servicer increased by $320 million,

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Note 1: The funding in the FY 1990 Capital Development Plan totalled $13.570 billion from FY 1987 through FY 1993, in FY 1990 dollars. Converting the FY 1990 plan to FY 1991 dollars would adjust that estimate by $453 million, for a total $14.023 billion.

Advanced Programs decreased by $52 million, and Orbital Debris Radar was transferred to the Construction of Facilities budget, which resulted in a decrease of $20 million in the Space Station R&D account. The reduction in Development reflects the transfer of the Polar Platform to the Office of Space Science and Applications (-$481 million), and the reduction of -$1.190 billion made to the Development program as a result of the rephasing of the baseline program. This reduction resulted from deletions, reductions, and deferrals of program content while maintaining the First Element Launch milestone in FY 1995 in a near-term constrained budget environment. Consequently, a significant portion of the Development program budget has been deferred to the post-FY 1993 timeframe. Major adjustments made include deletion of Space Station-unique EVA suits, converting from an AC to an all DC power system, changing from an oxygen/hydrogen to a hydrazine propulsion system, deferral of the global positioning system, rephasing facility capabilities, and descoping the Technical and Management Information System, the Software Support Environment, and the Space Station Engineering Integration Contract. The increase in FTS is due to change in the assumption in the FY 1990 budget that FTS would be a commercially developed system. After careful consideration of industry responses, the decision was made that FTS should be a government funded program. The reduction in Advanced Programs is due to a descoping of advanced systems studies and advanced development, and the addition of funding in FY 1991 in support of the space exploration initiative.

In Space Transportation Capability Development, the increase of $57 million is attributable to a change in the assumption in the FY 1990 budget that the Space Shuttle Orbiter-Station docking system would be commercially developed. Additional review indicated that this was not a feasible objective; therefore, the FY 1991 budget and Capital Development Plan includes requirements for a government-funded docking system.

2. Spaceflight, Control, and Data Communications

The decrease of $172 million in this account includes a reduction in Space Transportation Operations of $58 million and revised allocation of the Customer Data Operations System (CDOS) unique support of the Space Station Freedom. Both changes are driven by the transfer of the Polar Platform to the Office of Space Science and Applications as an integral element of the Earth Observing System (EOS). Last year's Capital Development Plan included funding for an Expendable Launch Vehicle (ELV) in support of the Polar Platform. This funding has been removed from the Space Station Program. In a similar manner, the Office of Space Operations CDOS allocation for the Polar Platform has been transferred from the Space Station program. The remaining funding in Space Transportation Operations covers the early costs of the Space Shuttle flights required for Station assembly.

3. Construction of Facilities

The increase of $111 million in Construction of Facilities (C of F) is primarily due to the inclusion of four major projects not in the C of F budget in last year's Capital Development Plan, minus the deferral of some facilities to later years following the program Configuration/Budget Review in late FY 1989. The Orbital Debris Radar had been previously included in the Space Station R&D budget, but has now been transferred to the C of F budget; this project will be funded in FY 1990. A neutral buoyancy laboratory will be constructed at the Johnson Space Center. It will be used for EVA simulations for astronaut training and EVA procedures development and validation for Space Station assembly and operations. At Kennedy Space Center, the Space Station Processing Facility will be built to provide the capability for pre-launch processing of Space Station elements, as well as refurbishment, retrofitting, and resupply of those elements regularly returned from orbit. Funding for these two facilities was not included in last year's plan, based on a proposed provision of the facilities through private sector investment. After evaluation of industry responses the decision was made that private provision of the facilities was not beneficial to the government. Finally, the Payload Operations Integration Center will be constructed at Marshall Space Flight Center. This facility will provide the capability to integrate payloads into the overall Space Station design, as well as providing the support necessary to establish and validate procedures for payload handling and operations.

4. Research and Program Management

The increase in funding estimates for Research and Program Management of $55 million through FY 1993 reflects an increase in FY 1991 in average compensation for civil servant salaries and benefits, and an approved increase in the allocated civil service personnel assigned to support the Space Station Freedom Program.

Appendix A: List of Acronyms

AC	Assembly Complete
CDOS	Customer Data Operations System
CDR	Critical Design Review
CoF	Construction of Facilities
FEL	First Element Launch
FTS	Flight Telerobotic Servicer
MTC	Man-Tended Capability
NBL	Neutral Buoyancy Laboratory
PDR	Preliminary Design Review
PMC	Permanently-Manned Capability
R&D	Research and Development
R&PM	Research and Program Management
SFCDC	Space flight, control and data communications
SSPF	Space Station Processing Facility

NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546

MAY 11 1990

Reply to Attn of

L:JJM:jl

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

In House Report 101-226, accompanying H.R. 1759, that authorized appropriations to the National Aeronautics and Space Administration (NASA), the Committee requested that NASA submit a report on Space Shuttle Efficiencies.

I am pleased to forward a copy of the report for your use.

Sincerely,

Martin P. Kress

Martin P. Kress
Acting Assistant Administrator
for Legislative Affairs

Enclosure

cc: Honorable Robert Walker

REPORT ON SPACE SHUTTLE EFFICIENCIES

Submitted to the
Committee on Science, Space, and Technology
U.S. House of Representatives

April 1990

INTRODUCTION:

House Report 101-226, accompanying H.R. 1759, the NASA Authorization Act of 1989, observed that "...the overall Shuttle budget continues at an annual level that is about $1 billion larger than the pre-accident budget." The Report goes on, "...current budget realities emphasize the need for adopting economies within the Space Shuttle program whenever such economies can be implemented with no adverse impact on quality or safety."

The Committee then directed NASA to conduct a study "to determine what efficiencies the Agency believes could be adopted within the space Shuttle program during the next five years..."

The following text summarizes the results of NASA's study.

The major cause of the approximately $1 billion increase in budget since Space Shuttle mission 51-L is the increase in personnel. This increase in personnel was required to implement the additional checks and balances incorporated into the Space Shuttle Program (SSP). These additional checks and balances were deemed necessary during the post-STS 51-L accident review to ensure identification and resolution of safety-of-flight issues. It is unlikely that resource requirements will ever be reduced to previous levels. However, the SSP is aggressively pursuing several cost avoidance options which will improve the operational support posture without compromising flight safety. A brief description of several of the more significant efforts, now underway, is provided herein.

a. **Flight Analysis Design Systems (FADS).** The Mission Operations Directorate at JSC is developing a new flight design system scheduled for implementation in FY93. The current flight design systems requires manual data entry and transfer via paper products for mission unique flight design, which by its nature, yields numerous opportunities for human error. Additionally, the current system has no engineering data archiving system for quality assurance, reuse, or retrieval. Once operational, the new system will be characterized by consolidated and reduced code and most manual mission data transactions will be altogether eliminated. The new system is being designed to provide a safer, more efficient flight design and analysis system. Productivity and efficiency gains are expected to offset additional manpower requirements resulting from higher flight rates by approximately 50 equivalent people per year. This efficiency is incorporated within the Agency's FY91 Congressional Budget.

b. **Advanced Solid Rocket Motor (ASRM).** The ASRM will have numerous improvements over the Redesigned Solid Rocket Motor (RSRM) including: increased performance margins, greater system reliability, and improved manufacturing repeatability. The improved manufacturing processes should result in significant cost per-flight reductions after the ASRM program enters its production phase.

c. **Alternate Turbopump Development (ATD).** This ATD program is being pursued to develop and certify an improved high pressure fuel turbopump (HPFTP) and high pressure oxidizer turbopump (HPOTP). Operating the Space Shuttle main engines (SSME's) equipped with the alternate turbopumps will significantly improve the safety margin in the SSME's. Objectives of the ATD program are to develop an alternate source of turbomachinery (interchangeable with the current SSME design), to achieve improved service life, to minimize operational costs, and to improve safety and reliability through innovations in design, inspectability, and maintainability. The alternate turbopumps should reduce operational costs by reductions in turbopump rebuilds and ground turnaround operations.

d. **Day of Launch I-Loads Update (DOLILU).** The SSP is actively pursuing a capability to design and build a flight trajectory based on actual winds measured prior to launch. This system is referred to as "Day of Launch I-Loads." This is estimated to improve mission launch probability by 10 percent over the existing capability. Cost savings should occur due to the reduction of the current system preparation and verification effort. Additional savings will accrue from the minimization of the mission unique I-load design to meet SSP performance and launch probability objectives.

When DOLIU's achieve full operational status, the SSP is projecting a potential cost avoidance due to the standardization of ascent flight design and integration system margin assessment. Avoidance of significant launch delay costs are expected as a result of this new capability and have been planned within the FY91 Congressional Budget.

e. **Turnaround Reduction.** An effort is in work to identify vehicle turnaround reduction opportunities. The effort includes revising the Master Verification Plan guidelines, and a review of the Operational Maintenance Requirements and Specification Document (OMRSD). Overall results of the OMRSD alteration are that requirements change notice (RCN) processing is about 95 percent complete and that shift reduction is estimated to be 135 parallel shifts. OMRSD changes are being incorporated and started with the STS-36 flow at KSC. All RCN processing is scheduled to be complete by STS-40. The goal of this effort is to reduce the number of days in an Orbiter Processing Facility (OPF) flow to 51 days/flow from the current average over 6 OPF flows, excluding first vehicle flows, of 91 days/flow. STS-36 had an OPF flow of 69 days.

f. **Automated Interface Control Documents.** The interface requirements data base (IRDB) is a system of computer hardware and software that will completely automate the Space Shuttle vehicle flight and ground interface design requirements and requirements change processing. IRDB eliminates the extensive manual processing and distribution of requirements documents and changes that characterize the present design control system. Projected savings in terms of equivalent person (EP) manhours indicate a decrease from 22 manyears for the manual system, to 16 manyears for the IRDB by October 1991.

g. **Space Station/Space Shuttle Commonality.** A joint Space Shuttle Program/Space Station Freedom Program Commonality Working Group is in the process of identifying and investigating potential common use items in order to minimize costs to NASA due to similar parallel development and/or production activities. The extent of potential common use systems and cost savings due to joint program specific commonality implementation is expected to be identified in the Spring. Specific savings are expected to be identified in the areas of environmental control and life support system, communications, television, extravehicular activity, crew systems, and data management.

h. **Shuttle Processing Data Management System (SPDMS) II.** SPDMS II is the descriptive title for a computer hardware, software, documentation, and processing system that will provide technical and management information support to Shuttle ground processing activities at the Kennedy Space Center (KSC). The project will significantly improve the work control system at KSC by providing faster, more accurate work scheduling , tracking, and approval to support the projected flight rate. SPDMS II will largely replace the manual, paper-oriented work tracking and control system which has been in use up to now in Shuttle as well as in past programs.

Except for commonality between the Shuttle and Station programs, the projected savings associated with these items have been incorporated in our cost projections for the out year budget requirements. As the Space Shuttle Program operating experience increases, we will continue to pursue system operations enhancements which will contribute to minimizing resource requirements without adversely impacting quality or flight safety.

NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546

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AUG 10 1990
Committee on Science, Space,
and Technology

AUG 10 1990

Reply to Attn of L:JJM:jl

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

In House Report 101-226, which accompanied H.R. 1759, the NASA Multiyear Authorization Act of 1989, NASA was requested to study the feasibility and cost of modifying all of the Space Shuttle orbiters with an automated deorbiting and landing system and to report the results of the study to the House Committee on Science, Space, and Technology and the Senate Committee on Commerce, Science and Transportation.

I am pleased to forward a copy of the report for your review.

Sincerely,

Martin P. Kress
Martin P. Kress
Acting Assistant Administrator
for Legislative Affairs

Enclosure

cc: Honorable Robert S. Walker

AUTOMATED SHUTTLE DEORBIT AND LANDING REPORT

Submitted to the
Committee on Science, Space, and Technology

U.S. House of Representatives
and the
Committee on Commerce, Science, and Transportation
United States Senate

April 1990

INTRODUCTION

House Report 101-226, accompanying the NASA Authorization Act of 1989 (H.R. 1759), states "In the safety area, the Committee believes that NASA should give serious consideration to modifying all of the orbiters so they can deorbit and land in a fully automated mode (i.e., without interaction by the crews). The committee requests that NASA study the feasibility, desirability, and cost of making such a modification and report the results of that study to the Committee...."

The following text summarizes the results of NASA's study.

FEASIBILITY

The effort required to provide an automated capability to recover a Shuttle will depend on the mission phase from which the capability is initiated. The mission phases considered are predeorbit, deorbit, entry, approach and landing and, derotation and rollout. It will also depend on the redundancy levels determined to be necessary. The following discussion assumes the avionics two fault tolerance normally required for the Space Shuttle.

PREDEORBIT - Designing a capability to function from any time in the on orbit mission phase would be the most difficult approach. During various periods of on orbit operations, much of the equipment necessary to effect entry and landing is powered off or disabled. These systems include:

Reaction Jet Driver Power
Rate Gyro Assemblies
Auxiliary Power Units
Payload Bay Doors
Flash Evaporators
Water Spray Boilers
Payload Systems (tilt tables, etc. required to safe the bay for entry)
Star Tracker Doors
Accelerometer Assemblies
TACAN, MSBLS Power
Orbiter Maneuvering System
Data Processing System

Parts of all these systems currently require manual switch activation for deorbit preparation. Automating the process would require interfacing these switching functions to the orbiter's general purpose computers.

This would require a minimum of two additional multiplexer/demultiplexer units (MDM's) and up to fifteen additional motor and power control assembly boxes for switching. Existing motor and power control boxes would require modifications. For purposes of redundancy, channelization of existing MDM's would have to be changed, and some existing functions transferred to the new units. This would avoid routing redundant paths through common failure points. Additional cold plate cooling would be required.

These modifications would require a very large engineering effort to integrate. Large changes would have to be made to both systems and applications software.

DEORBIT - If the vehicle could be assumed to be in a fully powered up and properly configured mode, as it is just prior to the deorbit burn, the task would be greatly simplified. Functions would have to be added to automate arming/pressurization of the orbital maneuvering system engines, starting the auxiliary power units, and taking them to normal pressurization. Additional requirements for entry and landing are described in the sections below. The deorbit unique capabilities would total about eight switching requirements, with multiple channels each for redundancy.

ENTRY - During the entry phase, the Shuttle is normally flown in an automatic mode. The only switching function required during this phase would be deployment of the air data probes, which occurs when the mach number is less than five. Channels for both the right and left probe deploy functions would be required.

APPROACH AND LANDING - For the approach and landing phase, the only switching functions requiring automation would be for arming and deployment of the landing gear. The Shuttle has an existing approach and landing guidance, which could be used in an automatic mode by the flight control system. Ground updates, based on radar tracking, to the onboard state vector could be used as a backup to the three TACAN receivers, which would provide full two fault tolerance for navigation in the terminal area energy management phase. During the final approach, the three microwave scanning beam landing system (MSBLS) receivers provide the required navigation accuracy. Although they do not provide the required two fault tolerance in all failure cases, it is probably not reasonable to consider adding a fourth receiver.

DEROTATION AND ROLLOUT - During the derotation, the drag chute, currently being developed for OV-105 and to be retrofitted to the other vehicles, serves as a significant aid to reducing slapdown loads, mitigating the effects of crosswinds and tire failures, and reducing rollout distance and brake wear. The drag chute controller box was designed with provisions in the circuit to facilitate automation, so that it can be directly connected to MDM discrete outputs. Once derotation was complete, the brakes would have to be applied, which, due to the characteristics of the signals being switched, would require a more complicated interface. Lateral steering can currently be performed automatically through the nosewheel steering system. This system is not fault tolerant; however, the upgrade planned for the OV-105 vehicle (to be retrofitted to the fleet) which provides one fault tolerance for the nosewheel steering requires manual reconfiguration to the backup system. Automating this reconfiguration is complicated by the requirement to automatically detect the failure, and to insure that the backup system is functioning properly before switching it in. Differential braking presently provides another backup to steering, but automating this capability would be a complex task.

The Backup Flight System (BFS), a software program run in the fifth orbiter general purpose computer which can take control of the orbiter in case of generic failures in the primary software, does not have autoland guidance, and so could not be used without substantial expansion. Difficulties associated with controlling it's engagement (presently a crew function), would make it seem unwise to try to provide a BFS capability.

DESIRABILITY

The following evaluations of desirability attempt to identify scenarios in which an automated capability would be valuable, evaluate the likelihood of these scenarios, and compare this probability with the impacts of developing the capability.

PREDEORBIT - A scenario which would call for an automated deorbit from a quiescent period of on orbit operations could be an accident, such as a fire, which could incapacitate the crew before they could prepare the vehicle for deorbit. A cabin depressurization should not be considered, since certain critical orbiter hardware will not operate in a vacuum long enough to effect entry. It is difficult to identify other failures which would not leave at least some crew members able to configure the necessary switches and initiate the deorbit burn. The risk from fire is considered to be low, since care has been taken in the design of the Shuttle to avoid the use of flammable or toxic materials. In the remote case it did occur and of such a magnitude to incapacitate the crew, the avionics necessary for deorbit and entry would undoubtly be affected as well.

DEORBIT - While the simple deorbit capability would be more straight forward to implement, it also covers a much smaller window of exposure, and so would offer little potential gain.

ENTRY - Implementing an automated capability for the entry and subsequent mission phases would protect a crew which could function in a weightless condition, but might become incapacitated as gravitational forces build during entry. This incapacitation might conceivably be caused by physiological effects of zero gravity on extended missions. However, for the automated capability to be required during the entry time frame, the incapacitation would have to be severe, as the mandatory crew functions during the entry phase are limited to a few switch throws and keyboard item entries, which are not particularly time critical.

APPROACH AND LANDING - Automating the arming and deployment of the landing gear is arguably more significant than the previous entry functions. It must be performed within a fairly limited time frame (less than four hundred feet altitude), and there is more risk that a crew suffering from physiological effects might not be able to reliably accomplish this function.

DEROTATION AND ROLLOUT - Braking is required to stop on concrete runways. This would not be necessary for lakebed landings. The complexity and cost of making the steering function redundant are discouraging factors. Since the piloting skill required to maintain lateral control after derotation is less than that required to land, there could be scenarios in which an autolanding might be required, and yet a partially disabled crewman could still control the rollout. No inflight faults in the existing steering system have been experienced. Many system failure modes that would cause loss of the first steering channel can be detected inflight before the entry, so that a crew could configure to the backup channel before being disabled by gravitational accelerations.

COST

PREDEORBIT - Costs have not yet been estimated for automation of all the systems which would be required if the deorbit had to be initiated from a quiescent state. Such a development would completely absorb certain critical engineering and software resources for a period of three to five years, which would have very substantial impacts on other program activities. Actual cost definition would require a substantial additional study.

DEORBIT - The cost of automating a fully configured vehicle for just the deorbit process is estimated at $20 million. It should be understood these estimates do not include the capability to deal with various malfunctions in systems described in the predeorbit section above.

ENTRY - The cost of automating the air data probe deployment across the fleet is estimated at $5 million.

APPROACH & LANDING - Automating the landing gear deployment is estimated at $8 million.

DEROTATION & ROLLOUT - The cost of automating the drag chute function has been estimated at $2 million. Automatic braking would require $15 million. Adding automatic switching between redundant modes of the nosewheel steering would cost $20 million.

COST SUMMARY - A summary of these costs is shown below. An additional MSBLS, automatic reconfiguration of nosewheel steering redundancy, and differential braking are not included as they are not considered cost effective. As the summary shows, cost estimates vary considerably depending on the mission phase in which the automated mode would begin.

($ in millions)

Starting from:	PREDEORBIT	DEORBIT	ENTRY	APPROACH & LANDING	DEROTATION AND ROLLOUT
Predeorbit functions	TBD				
Deorbit functions	20	20			
Air Data Probe Deploy	5	5	5		
Landing Gear Deploy	8	8	8	8	
Drag Chute Deploy & Jettison	2	2	2	2	2
Braking	15	15	15	15	15
TOTAL	TBD	50	30	25	17

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STIRLING COMMERCIALIZATION STUDY

FINAL REPORT

Volume I

by
National Aeronautics and Space Administration
Washington D.C. 20546

and

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

May 1990

Volume I of

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STIRLING ENGINE COMMERCIALIZATION STUDY

1.0 EXECUTIVE SUMMARY

The Stirling Commercialization Study was carried out in response to House Report 101-226 accompanying HR1759. The report language claims that "the Stirling engine may eventually contribute to a long-term solution to the Nation's emission problems" and that "supporters of the Stirling engine have proposed a Government and industry cost-sharing demonstration program." "To determine the optimal long-term sponsor for the Stirling engine" the report directed NASA "to participate in an interagency study including the Department of Energy, the EPA and the Air Force, in consultation with other interested agencies, to evaluate potential sponsorship of such a program." The other participating agencies were the Department of Transportation, the United States Army, and the United States Postal Service. The study was to "include the optimal size and scope of the demonstration fleet, a determination of the private sector contribution, and a mechanism for securing such funds." The report encouraged NASA to "consult with the private sector in developing the study plan." The following private sector organizations were consulted:

Cummins Engine Company, Columbus, Indiana
Deere & Company, Moline, Illinois
Ford Motor Company, Dearborn, Michigan
Gas Research Institute, Chicago, Illinois
General Motors Research Laboratories, Warren, Michigan
Hercules Engine Incorporated, Canton, Ohio
Kennedy Engine Company, Biloxi, Mississippi
Stirling Thermal Motors Inc., Ann Arbor, Michigan

In 1978 Congress passed the Automotive Propulsion Research and Development Act of 1978 (Title 3, PL95-238). In response the Department of Energy the Stirling engine as one of two new engines for technology development and selected the NASA Lewis Research Center as project manager for the Automotive Stirling Engine (ASE) Project, which began March 22, 1978. The goals of the DOE ASE program were to develop and verify the technology base necessary to meet the following propulsion system objectives: 1) at least a 30-percent improvement in fuel economy, 2) emission levels that meet or exceed the Federal research standards, 3) the ability to use a broad range of liquid fuels, and 4) suitability for cost-competitive mass production.

The project was carried out utilizing two generations of engines, Mod I ASE and Mod II ASE. The Mod I ASE was intended as a first experimental testbed engine. The Mod II ASE engine was intended, as the proof-of-concept engine, to incorporate all required technologies and to demonstrate the program goals. Mod I ASE's accumulated more than 20,000 hours of operation in laboratories, including more than 3,800 hours and 44,000 miles in vehicle demonstrations. Mod II ASE's have accumulated only 1,700 hours of operation, including about 500 hours and 7,300 miles of operation in a postal delivery van.

The Mod II ASE has successfully demonstrated multifuel operation and good drivability in a vehicle. In addition, the availability of low-cost, high-temperature materials needed for mass production has been established. However, the Mod II ASE in a vehicle has failed to demonstrate the fuel economy or emissions goals of the program. Mod II ASE fuel economy improvements (losses) were inconsistent as demonstrated by the wide range of results (from -5 to +13 percent relative to the spark ignition engine). Emission results were marginal for today's standards and fall far short of projected goals likely to be required by the time the engine could reach the market.

In view of these results the participating agencies and industry organizations contacted have concluded that the proof-of-concept Mod II ASE is not ready for prototype commercial demonstration. The responses have indicated that such a proof-of-concept engine must first demonstrate the basic goals of the program before a commercial demonstration can be justified. As a consequence, none of the Government agencies have indicated a desire to participate in long-term sponsorship of the Mod II ASE commercialization effort at this time.

These determinations, along with the agency and private industry responses, lead to the following findings regarding Stirling engine commercialization:

1. **The Mod II ASE has not achieved a level of performance or value that would interest any Federal agencies or engine/automobile manufactures in a commercial demonstration program.** Neither the Mod II ASE development effort by the engine developer nor the proof-of-concept evaluation conducted with potential users achieved all of their goals, although the proposed engine designs were completed. The fuel economy goals of the program were not met. Although the emissions reduction potential appears to have some promise, it has not been fully determined, nor has the emissions durability of the Mod II ASE been verified. Although the Mod II ASE meets the current level of Federal emissions standards, any new alternative engine such as Stirling must be directed to meet the Federal standard anticipated when the engine will be introduced into the marketplace.

2. **Introducing any new alternative engine directly into the automobile in the near term is highly unlikely because of the large capital investment, the high risk, and the difficulty of predicting manufacturing costs.** Instead, initial application in a niche market at relatively low production quantities may build the confidence and experience needed to support a later mass production decision.

3. **Advancing the program beyond the proof-of-concept phase must involve both the engine and vehicle manufacturer.** The Mod II ASE was intended to offer improved manufacturability and lower cost, the engine and vehicle manufacturers will need to decide what further improvements are necessary for initial market entry.

4. **Commercial demonstration plans must be defined primarily by the engine manufacturer and developer and the user organizations** (both private and Government) and could involve anywhere from 40 to 250 engines.

2.0 INTRODUCTION

This study was carried out in response to House Report 101-226 accompanying HR 1759, the NASA Multiyear Authorization Act of 1989. This report language claims that the automotive Stirling engine may eventually contribute to a long-term solution of the Nation's emission problem, and notes that supporters of the automotive Stirling engine have proposed a Government and industry cost-shared demonstration program. As the report directed, NASA participated in an interagency study with the United States Air Force, the Department of Energy, the Environmental Protection Agency, and other interested agencies to determine the potential benefits of such a demonstration program and the optimal long-term sponsor or sponsors if such a demonstration program were to be performed. This study was also to address and to identify the optimal size and scope of a demonstration fleet, the private and public sector contributions, and a mechanism for securing such funds. In addition, the report encouraged NASA to consult with the private sector in developing the study plan. The report language is included as appendix A.

2.1 STUDY OBJECTIVES

The following study objectives were defined on the basis of the congressional report language:

1. **Determine the optimal long-term Government sponsor** or sponsors, if any, for automotive Stirling engine commercialization. Agencies to be considered would include the Department of Energy (DOE), the Environmental Protection Agency (EPA), the Department of Transportation (DOT), the National Aeronautics and Space Administration (NASA), the United States Air Force, and the United States Postal Service (USPS).

2. **Determine the optimal size and scope of an automotive Stirling engine demonstration program,** if one appears advisable. The number of engines and vehicles and the demonstration service and length of demonstration should be defined. Past demonstration experience and industry needs should be considered in defining an effective demonstration program.

3. **Determine a mechanism for securing funds,** if a demonstration is performed. This should include the procurement approach, the method of industry contributions, and cost sharing.

4. **Determine the extent of the private sector contribution** that will best promote commercialization. This would include an effective balance of risk, commitment, and ultimate benefits.

5. **Assess the status of Stirling technology** and define the potential of long-term Stirling technologies.

This last objective, although not specifically required under the report language, was added in order to put the possible demonstration program in the appropriate perspective of Stirling technology status both current and future.

2.2 BACKGROUND OF STIRLING ENGINE

Stirling engines are classified as either "kinematic" Stirling or "free-piston" Stirling engines. Both configurations operate on the same thermodynamic cycle, called the Stirling cycle.

The kinematic Stirling engine was invented by a Scottish clergyman, the Reverend Robert Stirling in 1816. With the temperature limits of materials available in the 19th century (600 to 800 °F), it could not compete effectively with the steam engine. Except for some water-pumping applications around the turn of the century, it did not receive any significant development attention until the 1940's. Then the N.V. Philips Gloeilampenfabrieken of the Netherlands undertook its development. In the 1970's, first General Motors and then Ford Motor Company conducted Stirling technology efforts under license agreements with N.V. Philips. Their efforts included a Stirling electric vehicle by GM and a Stirling-powered Ford Torino vehicle by Ford. However, both companies ultimately chose not to continue their Stirling work.

United Stirling AB, Malmo, Sweden, an early licensee of N.V. Philips has developed several Stirling engines for a variety of applications, though none has yet been commercially successful. United Stirling was the original source of Stirling technology for the DOE Automotive Stirling Engine Program as discussed later. In recent years United Stirling has been absorbed by Kockums Shipyard, Malmo, Sweden, which is developing Stirling engines for submarine applications.

Stirling Thermal Motors, Ann Arbor, Michigan, another N.V. Philips licensee, was formed in 1979 by Dr. R.J. Meijer, who formerly headed the N.V. Philips Stirling engine program in the Netherlands. STM's early development concentrated on engine designs for stationary and solar applications. During 1989 STM has directed their engine design toward the automotive application.

The free-piston Stirling engine was invented by William Beale at Ohio University in 1962. Up to this point all Stirling engines had been kinematic Stirling engines (see definitions, appendix B). Beale's early work resulted in small-scale fractional horsepower engines that demonstrated the operating principles of the basic free-piston engine.

The free-piston engine has a major advantage over the kinematic engine in that it has only two moving parts (a displacer piston and a power piston), which ride on noncontacting gas bearings and can be hermetically sealed thereby increasing the free-piston Stirling's potential for high reliability and very long life.

Only a few organizations in the United States have been active in developing the free-piston Stirling engine. These include Sunpower, Incorporated, of Athens, Ohio; Mechanical Technology Inc. (MTI) of Latham, New York; and Stirling Technology Company (STC) of Richland, Washington. Recently Cummins Engine Company of Columbus, Indiana, has teamed with Sunpower; and Westinghouse Electric Company of Pittsburgh, Pennsylvania, has teamed with STC in efforts to commercialize the free-piston Stirling. By 1982, a few free-piston engines had been built in the 3- to 4-kilowatt size range. Most recently a space power demonstration engine was designed and built by MTI for NASA. This engine has now delivered more than 22 kilowatts of output power. Today MTI is continuing to develop a space power engine for NASA in the 25- to 50-kilowatt (33- to 67-horsepower) size range. Free-piston Stirling engines are currently under development for the solar terrestrial power application in sizes ranging from 5 to 25 kilowatts.

2.3 ATTRIBUTES OF STIRLING ENGINE

The Stirling engine has a number of attributes that make it attractive, in theory for a variety of engine applications. First, Stirling engines are highly efficient. MTI has claimed that with current technology, automotive Stirling engines should provide fuel economy improvements of at least 30 percent compared with standard internal combustion engines, although the engines MTI has built do not achieve that. Next, Stirling engines have a broad multifuel capability and will operate on essentially any source of heat ranging from nuclear to solar and including liquid, solid, and gaseous fuels. When heat is provided by combustion of a liquid fuel, the Stirling engine's emissions meet the current level of Federal standards without a catalytic converter. This low-emission characteristic stems from the external continuous-combustion system operating at essentially atmospheric pressure. Other attributes due to the external combustion system include reduced noise without a muffler and reduced infrared signature and structural noise. The latter two attributes are of interest to the military. Finally, because Stirling engines require only one igniter, no catalytic converter, and no muffler, they have the potential for very low maintenance costs. Moreover, since the lubricating oil does not come in contact with the products of combustion, there is no need for changing oil or oil filters.

2.4 BACKGROUND AND OBJECTIVES OF ASE PROGRAM

In 1975, the Environmental Protection Agency's Automotive Heat Engine Program selected the Stirling engine as one of the promising candidates for achieving national goals for automotive emissions, fuel economy, and multifuel capability. Subsequently, Congress passed the Automotive Propulsion Research and Development Act of 1978 (Title 3, PL 95-238). The Act specifically directed the Department of Energy (DOE) to "establish and conduct new projects and accelerate existing projects which may contribute to the development of advanced automobile propulsion systems and give priority attention to the development of advanced propulsion systems. With appropriate attention to those advanced propulsion systems which are flexible in the type of fuel used." The Stirling engine and the gas turbine engine were the two "new" alternative engines selected by DOE for technology development in response to PL 95-238.

The NASA Lewis Research Center was selected by the Department of Energy (DOE) as project manager for the Automotive Stirling Engine (ASE) Project. Consistent with PL 95-238 and specific guidelines provided by DOE's Office of Transportation Systems, the goals of the DOE ASE program were to develop and verify the technology base necessary to meet the following propulsion system objectives and to provide confidence in that technology base by verifying the technology in appropriate testbed engines:

1. At least a 30-percent improvement in fuel economy (miles per gallon) over a production vehicle of the same class and performance powered by conventional spark ignition engines (based on equal heating value content of the fuel used).

2. Emission levels that meet or exceed the most stringent Federal research standards; 0.4, 3.4, 0.4, and 0.2 g/mile of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulates, respectively.

3. The ability to use a broad range of liquid fuels derived from crude oil as well as synthetic fuels from coal, oil shale, and other sources.

4. Suitability for cost-competitive mass production.

At the outset of the NASA ASE project certain technologies had to be advanced in order to meet the propulsion system objectives. Specifically, these technology objectives were as follows:

1. To develop high-temperature metal alloys low in content of strategic materials (particularly cobalt).

2. To develop the technology for seals with leakage, friction, and life characteristics suitable for the application.

3. To develop the technology necessary for low-emission combustion systems.

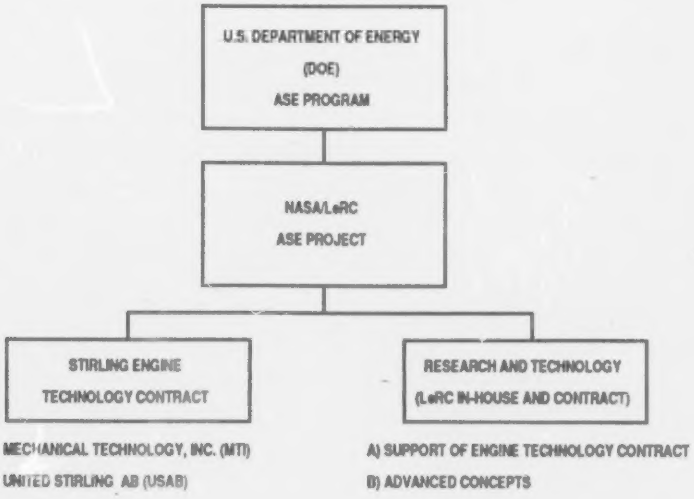

U.S. DEPARTMENT OF ENERGY
(DOE)
ASE PROGRAM
NASA/LeRC
ASE PROJECT
STIRLING ENGINE
TECHNOLOGY CONTRACT
RESEARCH AND TECHNOLOGY
(LeRC IN-HOUSE AND CONTRACT)
MECHANICAL TECHNOLOGY, INC. (MTI)
UNITED STIRLING AB (USAB)
A) SUPPORT OF ENGINE TECHNOLOGY CONTRACT
B) ADVANCED CONCEPTS

Figure 1 - DOE program/NASA project organization.

4. To develop component technologies required to reduce engine cost and weight and to improve engine performance and life in support of the program objectives.

5. To identify and evaluate concepts, not expected to mature by 1987, that may significantly affect engine life, cost, or performance.

The DOE-sponsored, NASA-managed ASE project involving the kinematic Stirling engine began on March 22, 1978. The basic organization of the program is shown in figure 1. The chronology of the DOE ASE program is given in appendix C. The primary engine development effort was conducted by a team consisting of Mechanical Technology Inc. (MTI), Latham, New York, and United Stirling of Sweden (USAB), Malmo, Sweden, under contract to the NASA Lewis Research Center. As the prime contractor, MTI was responsible for overall contract management, development of component and subsystem

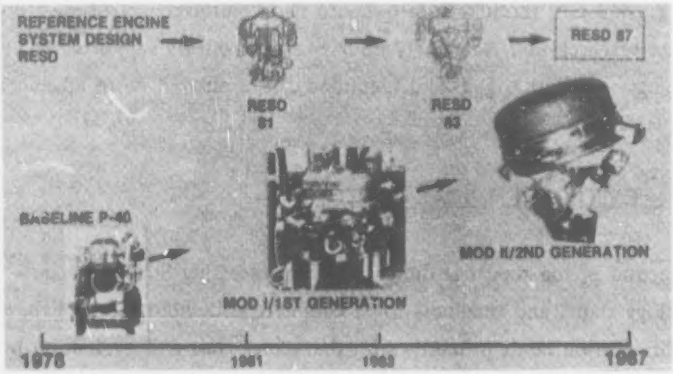

REFERENCE ENGINE
SYSTEM DESIGN
RESD
RESD 81
RESD 83
RESD 87
BASELINE P-40
MOD I/1ST GENERATION
MOD II/2ND GENERATION
1978
1981
1983
1987

Figure 2 - Engine development contract approach.

technology, and the transfer of European Stirling engine technology to the United States. USAB was responsible for in-engine technology verification and for providing the initial base of Stirling technology to the program.

The technical approach to the project is illustrated in figure 2. The contract effort was focused on a reference engine system design (RESD) intended to represent the best engine that could be designed to meet the program goals by using the technologies reasonably expected to be developed over the life of the program. Two generations of engines were planned in the development of the reference engine. The Mod I engine used technology available early in the program and was a first step toward the RESD. The Mod II engine was then planned to incorporate all of the technologies required for the reference engine design and was to be a proof-of-concept version of the RESD. In 1981, the Mod II engine was deleted from the program and emphasis was placed on demonstrating the RESD technologies in improved versions of the Mod I engine. The Mod II engine was restored to the program in 1984, as a congressional add-on.

In addition to overall project management of the DOE ASE program, NASA Lewis carried out, through both in-house and contracted activities, a number of separate research and technology efforts. These efforts supported the technology verification goal and identified and evaluated more advanced Stirling concepts.

3.0 SUMMARY OF TECHNICAL STATUS

This section of the report is directed toward assessing Stirling engine technology status and readiness for a commercial demonstration. Therefore, the ASE portion deals primarily with the vehicle test and evaluation programs, rather than the details of component development and engine dynamometer tests. The status of other Stirling technologies is presented for completeness and to display some technical options.

3.1 STATUS OF ASE PROGRAM

The Mod I ASE (fig. 3) is a four-cylinder double-acting engine with dual crankshafts. It incorporates one canister type of regenerator and cooler per cylinder. As the first engine designed in the program, and in view of high-temperature materials considerations, it was designed for a heater head temperature of 720 °C rather than the 820 °C planned for the RESD. Because the Mod I was designed as a proof-of-concept laboratory testbed engine, it is too large and heavy for passenger car application. The Mod I ASE was installed and tested in light-duty trucks, however.

Figure 3 - Mod I ASE.

The Mod II ASE (fig. 4) is considered to be a proof-of-concept engine also and was specifically designed to be installed in a 1985 GM Celebrity automobile with manufacturability as a key consideration (ref. 1). It is a four-cylinder, double-acting engine arranged in a V-configuration with a single crankshaft and was designed to operate at an 820 °C heater head temperature. It incorporates an annular regenerator and cooler wrapped around each cylinder and is substantially smaller and lighter than the Mod I engine (fig. 5).

Seven experimental Mod I engines were produced, including several improved versions. These seven engines have accumulated over 20,000 hours of operation. General Motors Research Laboratories successfully tested one engine in an American Motors Spirit vehicle in the Industry Test and Evaluation Program (ITEP) in 1984. Also in 1984 as part of ITEP, Deere & Co. successfully tested a Mod I engine in one of their test cells. Approximately 4,300 hours and 51,000 miles were accumulated in vehicle demonstration projects with the Mod I and Mod II ASE's throughout the program.

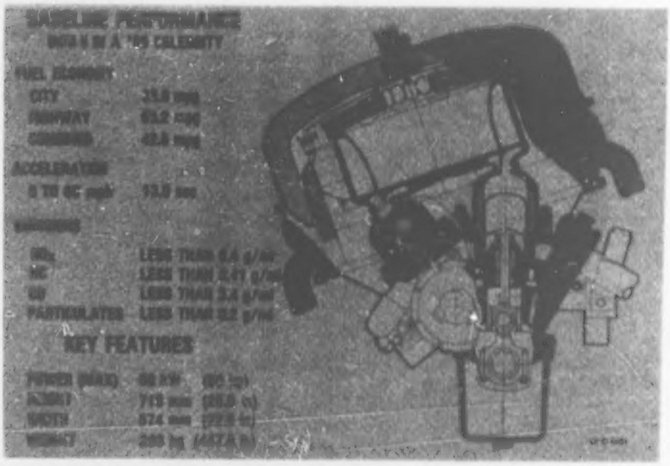

BASELINE PERFORMANCE
FUEL ECONOMY
CITY
HIGHWAY
COMBINED
ACCELERATION
LESS THAN
PARTICULATES
KEY FEATURES
POWER (MAX)
WIDTH

Figure 4 - Mod II ASE.

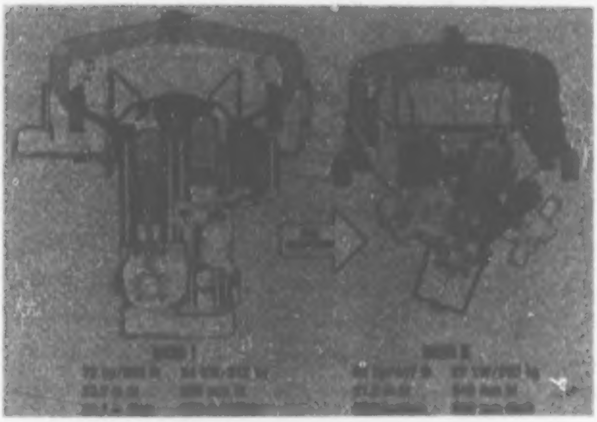


Figure 5 - Comparison of Mod I and Mod II ASE's.

The latter demonstrations were sponsored by the NASA Technology Utilization Office in cooperation with the Department of Energy, the U.S. Air Force, Deere & Co., the American Trucking Associations, and later the United States Postal Service (USPS). Approximately 3,800 hours and 44,000 miles were accumulated in vehicle demonstration activities with Mod I engines throughout the ASE program. The breakdown of these hours is provided in table I.

TABLE I - MOD I ASE VEHICLE EXPERIENCE

	Time, hr	Distance, miles
Lerma automobile	[a]150	[a]2,300
Spirit automobile	1,237	13,763
C-30 Van	1,429	8,804
D-150 Pickup truck	~ 1,000	~ 19,000
	~ 3,800	~ 44,000

[a] Estimated

Four Mod II engines were planned to be built and tested. Three engines were actually built and in the final years only two engines could be supported.
Mod II ASE's have accumulated a total of 1,700 hours of operation, including about 500 hours and 7,300 miles of operation in a USPS delivery van.

3.1.1 Industry Test and Evaluation Program

As part of the DOE/NASA program an Industry Test and Evaluation Program (ITEP) was begun in 1983 to obtain an independent evaluation of the Mod I ASE by automobile and engine manufacturers. The Government offered to loan Mod I engines to industry participants if the participants would conduct the tests and evaluations at their own expense. Two companies (GM and Deere) accepted the Government offer and tested Mod I engines in the summer and fall of 1984, respectively.

General Motors Research Laboratories (GMRL) in Warren, Michigan, requested that the engine be installed in a vehicle to allow a comparison with an existing vehicle system. The engine was installed in a 1981 Spirit and delivered to GM on April 24, 1984. GMRL personnel conducted a three-phase test program that included

1. Emissions and mileage tests using a fuel-based mass system that allowed an assessment of emissions for individual modes of each cycle;

2. Cooling system evaluation in a wind tunnel,

3. Driver evaluation on a test track,

The Mod I ASE installed in the Spirit vehicle successfully completed 54.7 hours of operation and 1,062 miles at the GMRL facilities. Results of these tests were documented in a GMRL report (ref. 2). The following highlights of these results include quotes from the GMRL report:

1. There were no major hardware failures - reliability "was remarkable during the 54.7 hours of testing."

2. Current Federal emissions standards were met with "a comfortable margin" without a catalytic converter.

3. Acceleration times were considered sluggish by GMRL personnel and "suffered severely at highway speeds."

4. "The engine passed standard cooling tests with ease" (oversized radiator).

5. High-idle fuel flow and the cold-start penalty were identified as major contributors to miles per gallon (mpg) shortfall on the urban cycle.

Emission, mileage, and acceleration results from the GMRL tests are presented in table II.

TABLE II - EVALUATION OF MOD I ASE BY GENERAL MOTORS (1984)

Vehicle	Test weight class	Emissions, g/mile			Mileage, mpg			Acceleration, sec	
		HC	CO	NO_x	Urban	Highway	Combined	0-60	50-70
Chevette	2500	0.30	0.99	0.82	28.4	40.4	32.8	18	13.5
Spirit ASE[a]	2500[b]	.22	1.92	.49	22.3	40.7	28.0	18.8	19.3
Spirit ASE[a]	3250[b]	.26	1.87	.59	20.5	34.7	25.1	23.5	21.0
Current emissions standards		0.41	3.40	1.00					

[a] Stirling engine and vehicle system not optimized

[b] Tested on a chassis dynamometer that simulated various test weight classes (TWC)

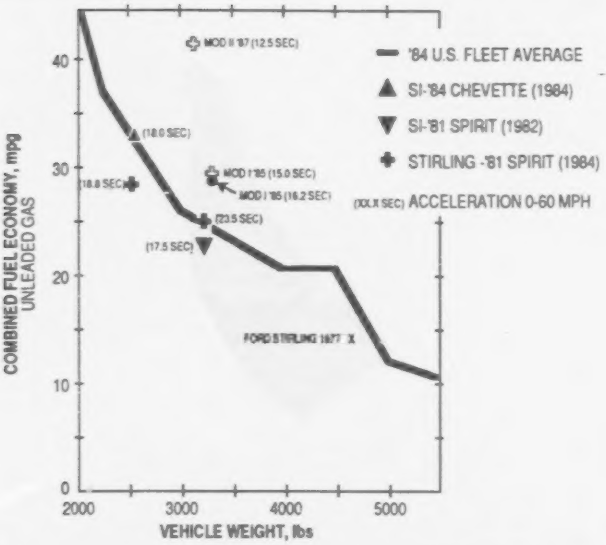


Figure 6 - Comparison of various Stirling powerplants.

Figure 6 places the fuel economy results in perspective. The solid line is the 1984 U.S. fleet average fuel economy. The solid cross symbols are the GMRL test results for the two different test weights run by General Motors. The open cross symbols represent fuel economy projections, first for an improved Mod I in the Spirit vehicle in 1985 and then (at the top of the chart) for the Mod II engine projected for 1987. The solid circle symbol represents actual test data for the Mod I engine in the Spirit in 1985. Because of the changes in the program and the emphasis on the vehicle demonstration aspects, the Mod II engine has never been installed in a passenger car. Thus, a test data point to compare against the Mod II projection is not available. General Motors does not believe Stirling can compete as an automobile engine but wishes to stay informed on Stirling and would be willing to test and evaluate a future Stirling vehicle.

Deere & Company, Moline, Illinois, evaluated a Mod I ASE in a Deere test cell in Waterloo, Iowa, in September and October of 1984. The engine operated for 37 hours with no major hardware failures and was started and operated on gasoline, diesel fuel, and JP-4 without changes to the control or combustor systems. With diesel fuel a significant ignition delay resulted in sooting of the air preheater. Limited noise data were taken although the test cell was not equipped for taking quantitative acoustic data. Qualitative results indicated that the Stirling at full power made no more noise than a normal diesel engine at idle. Tests were run at various heater and cooler temperatures with the predicted effects on power and efficiency. Test results and comparisons with diesel engines are described in detail in the Deere report (ref. 3). On the strength of these test results, Deere elected to participate in the NASA TU Demonstration Project described below as the potential engine manufacturer.

3.1.2 NASA Technology Utilization Demonstration Project

The NASA Technology Utilization Demonstration Project was funded by the NASA Technology Utilization (TU) Office and DOE as an adjunct to the ASE program. It was directed toward placing commercial manufacturers and users "on the path to commercialization" of the Mod II ASE. The demonstration project was cofunded by an industry-Government team that included NASA Lewis, the Department of Energy, the Department of the Air Force, Deere & Company, Mechanical Technology Inc., the American Trucking Associations, and later the United States Postal Service. As the prime ASE contractor, MTI was responsible for implementing the NASA TU Demonstration Project. A multiyear, multiphase demonstration program was created by the industry-Government team and is described in detail in reference 4. The primary objectives of the demonstration project were:

1. To obtain early operation and performance data while gaining initial experience in operating the Stirling engine in a typical user environment,

2. To evaluate the Stirling engine under realistic conditions and establish Stirling integrity, reliability, and durability,

3. To accelerate the development of Stirling engines and enable the earliest possible use of the second-generation Mod II ASE. Prior to the TU-sponsored demonstrations, the kinematic Stirling had been virtually a testbed engine and had never been committed to operation in a "real world" environment.

Phase I of the project involved operating a first-generation Mod I Stirling engine for up to 1,000 hours on unleaded gasoline and JP-4 aircraft fuel in an Air Force van under realistic conditions. Langley Air Force Base was chosen because it had an Air Force evaluation team (the Management and Equipment Evaluation Program, or MEEP) and because of the moderate Virginia climate.

Phase II of the project called for up to 1,000 hours of operation with a first-generation engine (Mod I at 775 °C) installed in a van operated in different climate and user conditions. Phase III called for a second-generation engine (Mod II at 820 °C) installed in a van and tested on the basis of the results of phase I and phase II.

For phase I the Air Force provided a 1986 General Motors multistop delivery van (fig. 7) powered by a standard 6.2-liter V8 diesel engine developing 145 horsepower at 3,600 rpm. The vehicle had a curb weight of 6,800 pounds and a maximum gross weight of 8,600 pounds. The 6.2-liter V8 diesel engine was replaced with the 72-horsepower Mod I Stirling engine. The Air Force delivery van was operated by regular Air Force personnel assigned to the 27th Aircraft Maintenance Unit (AMU) of the Tactical Air Command at Langley Air Force Base. The multistop van was designed to transport personnel and light cargo in a stop-and-go duty cycle. The multistop was used for the "expediter" mission by the 27th AMU, which maintains 15 to 20 fighter aircraft on the Langley flight line. The evaluation was for 10 months, from September 1986 through June 1987 (refs. 5 & 6). More than 1,100 hours and 4,000 miles were successfully logged with the expediter mission.

The Stirling-powered multistop van was operated on unleaded gasoline, JP-4 aircraft fuel, and diesel fuel during the 10-month evaluation period (fig. 8). The multistop successfully towed a variety of support equipment without difficulty. Moreover, Air Force personnel stated that the operation was "not a big deal" and was "better than anticipated." MTI support personnel were available to the Air Force on a daily basis to troubleshoot and to make minor repairs required during the evaluation.

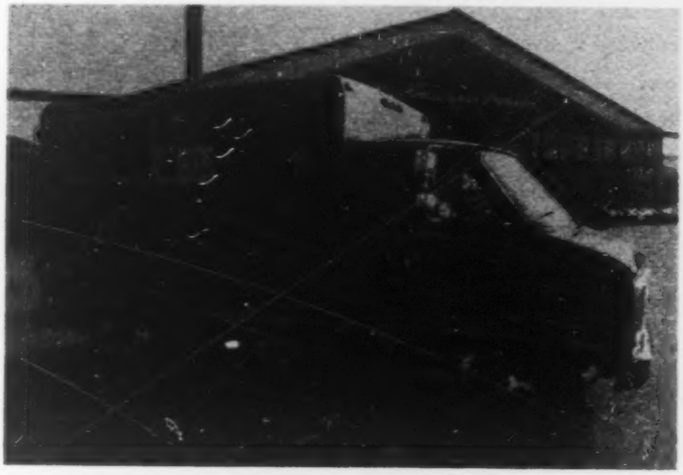


Figure 7 - Air Force multistop delivery van.

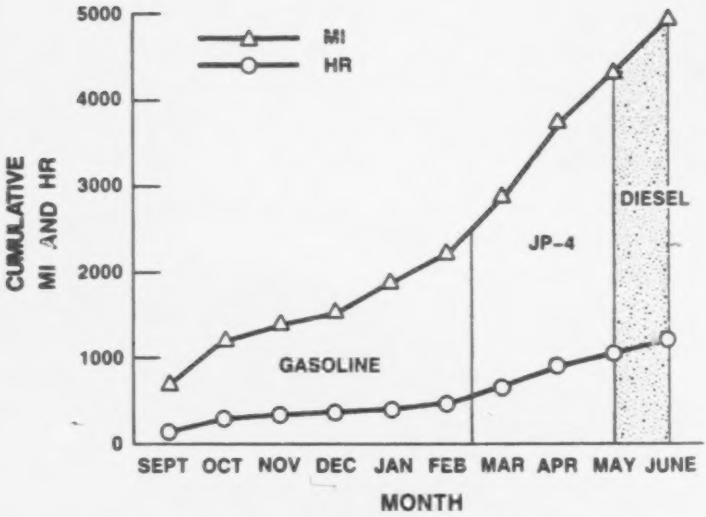


Figure 8 - Operating history of Stirling-powered multistop van.

The multistop van was to be available on a 24-hour basis, as needed by the Air Force. Availability of the van ranged from 55 percent during the early months to an average of 86 percent at the completion of the operational period at Langley. This was considered good for a single-unit demonstration at that stage of development. Vehicle operation was limited to the Langley flight line, where the authorized speed is 15 to 25 mph, and to the base, where the authorized speed is 35 mph. At times the vehicle usage ranged from only a few minutes a day to continuous around-the-clock operation during Air Force readiness exercises. Air Force personnel found the Stirling-powered multistop van to be as reliable as a standard vehicle for the expediter mission.

Following operation at Langley the van was taken to Deere & Company's plant in Moline, Illinois, and placed in service for Deere's local interplant mail delivery, where it accumulated an additional 209 hours of operation.

For the phase II effort a 1987 Dodge D-150 pickup truck was modified for operation with an upgraded Mod I Stirling engine (fig. 9). A 225-cubic-inch (3.7-liter) Slant 6 engine (95 horsepower) was replaced with the Stirling engine. Many of the lessons learned from earlier phase I operations were incorporated in this engine/vehicle build.

The D-150 pickup truck was operated at four Air Force bases for about two months time and 200 operating hours at each base and was driven from base to base on the highway (ref. 7).

The bases and the respective missions were Langley Air Force Base, flight line maintenance mission; Eglin Air Force Base, Ft. Walton Beach, Florida, housing

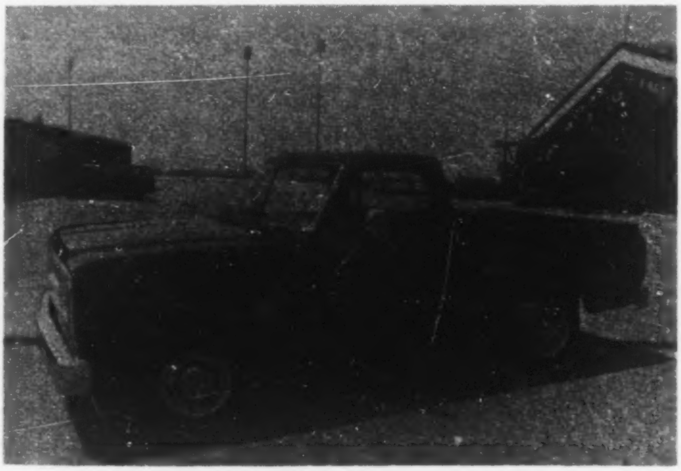
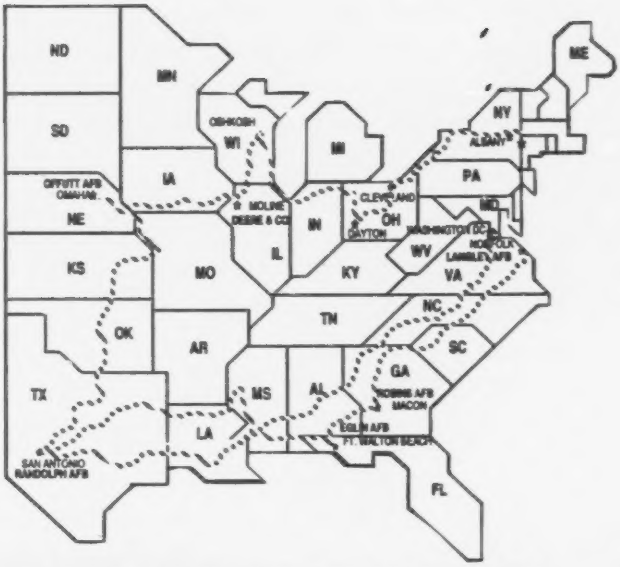


Figure 9 - Air Force D-150 pickup truck.


ND
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LA
SAN ANTONIO
RANDOLPH AFB
ME
NY
ALBANY
PA
MD
CLEVELAND
OH
DAYTON
WASHINGTON DC
WV
NORFOLK
LANGLEY AFB
VA
NC
SC
GA
ROBINS AFB
MACON
EGLIN AFB
FT. WALTON BEACH
FL

Figure 10 - Major trips made by D-150 pickup truck.

inspection; Randolph Air Force Base, San Antonio, Texas, base taxi service; Offutt Air Force Base, Omaha, Nebraska, civil engineering delivery service. In addition, one side trip was made when the vehicle was driven by Air Force personnel from San Antonio, Texas, to Washington, DC, for congressional hearings in the spring of 1988. In all cases the vehicles were driven by regular Air Force personnel. No drivability problems were encountered either in local urban operation or on the highways.

Figure 10 is a map showing the major trips made by the D-150 pickup truck. While the D-150 was at Eglin Air Force Base, it was tested in the Eglin climatic chamber, where it was subjected to temperatures from 10 to 120 °F. This test consisted of engine startup and warmup operation. Results were encouraging in that no unusual external hydrogen leakage occurred and no oil pressure problems were observed. While at Randolph Air Force base the

D-150 pickup truck was taken to Southwest Research Institute (SwRI), San Antonio, Texas, and tested for emissions and fuel economy. Costs for this testing were shared by Deere & Co. and SwRI.

Following the completion of in-service evaluation at the various Air Force bases, MTI made arrangements to have the Mod I D-150 tested by the State of Colorado in Denver. This test was aimed at assessing emissions when operating on 11% methyl tertiary butyl ether (MTBE), an oxygenated fuel designed to reduce CO emissions under high-altitude, low-temperature conditions. Before taking the vehicle to Colorado, MTI returned it to SwRI for some preliminary evaluation and adjustments with the 11% MBTE fuel before the Colorado tests.

In addition MTI took the Mod I D-150 to the U.S. Army Tank Automotive Command, Warren, Michigan, where it was evaluated for infrared signature.

For the phase III effort, a Mod II engine (nominal 73 horsepower) was installed in a 1987 USPS delivery van called a Long Life Vehicle (LLV), shown in figure 11. Figures 12 and 13 show the Mod II engine fully assembled with auxiliaries and transmission ready for installation. In this installation it replaced the 2.5-liter (92 horsepower) "iron duke" engine. This was the same engine that was originally planned to be replaced in the 1985 Celebrity vehicle. The Celebrity installation was dropped from the program in August 1987 because of lack of interest by the automotive companies; however, at the same time, Deere & Co., the potential manufacturer, was participating in the NASA TU Demonstration Project and expressing a strong interest in the light-duty truck/delivery van application. Deere believed this application could be an excellent niche market that might allow initial commercialization of Stirling. It was believed at that time that commercialization of Stirling in a low-volume production, over a period of time, could eventually lead back to a wider scale automotive application.

Figure 11 - USPS Long Life Vehicle.

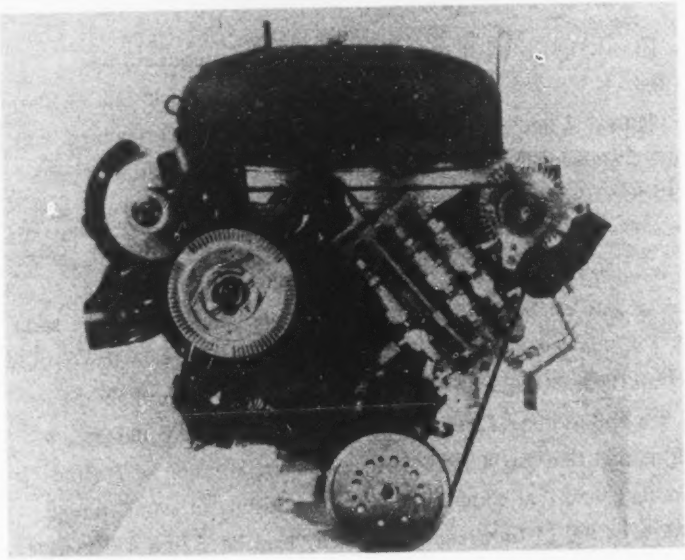

Figure 12 - Mod II ASE (front view).

Figure 13 - Mod II ASE (side view).

As the DOE program was being closed out, the USPS LLV was sent to the United States Postal Service, Engineering and Development Center, Merrifield, Virginia, for in-service evaluation (ref. 8). USPS conducted engineering tests during October 1989 and then placed the vehicle in actual mail delivery service. This service included combined curbline and park-and-loop mail delivery routes at the Vienna, Virginia, post office during November and December 1989. While providing normal mail delivery service, the Stirling-powered van operated on unleaded gasoline for about 44 hours/276 miles during November and on diesel fuel for about 29 hours/310 miles during December. Operators said they found no difference in drivability of the vehicle compared with the standard-spark-ignition-engine-powered vehicle. However, a number of system-related debugging problems occurred and low-temperature startups again became a problem during the evaluation period. This was not unexpected in view of the lack of debugging activities and cold-start development prior to this evaluation. Post engineering tests were conducted by the USPS at the conclusion of their evaluation period in late December 1989. A total of 123 hours of operation and 1,955 miles were accumulated on the van during the three-month postal service evaluation period.

3.1.3 Summary of Results

A variety of operating characteristics of the kinematic Stirling engine were evaluated and assessed during the ASE project and the subsequent TU demonstration effort. This section addresses the various characteristics observed and the status of the technology as it currently exists.

3.1.3.1 Drivability. - Early in the DOE program the automotive industry was skeptical of the potential of Stirling to achieve acceptable drivability. All vehicle evaluations, however, from the Spirit tested by GM under the ITEP program through the three vehicles tested in the NASA TU program, exhibited good drivability. The Mod I D-150 pickup truck was driven by a wide variety of personnel under a wide range of operating conditions ranging from flightline service to housing inspection to base taxi. The D-150 pickup truck was also driven on the highway at normal highway speeds when moving between the four Air Force bases and when driven from Texas to Washington, DC. In all cases the D-150 drivability was considered as good as or better than that of the standard vehicles.

3.1.3.2 Fuel economy. - Fuel economy results for both Mod I and Mod II ASE engines are included in appendix D. To date, these results are incomplete and inconclusive. Stirling engines have demonstrated fuel economy gains (losses) relative to the standard spark ignition engine of from -5 to +14 percent as determined by standard EPA urban/highway fuel economy tests. The ASE development could be further optimized, but conventional internal combustion engines also continue to improve, perhaps making the 30 percent goal an unreachable moving target.

The Mod II ASE (nominal 80 horsepower) was designed and optimized to replace the 2.5-liter (92 horsepower), four-cylinder "iron duke" engine in the 1985 Celebrity vehicle. Design projections predicted a fuel economy improvement of 32 percent for the Stirling-powered Celebrity compared with the iron-duke-powered Celebrity. Analysis of the Mod II ASE design in the USPS van resulted in a predicted fuel economy improvement of only 20 percent compared with the spark-ignition-engine-powered van. The predicted reduced fuel economy improvement of only 20 percent resulted from differences in engine/vehicle matching (actual tests showed a 2 to 5 percent loss). In addition, the Mod II ASE installed in the USPS van was somewhat different than the original design. Limited DOE funds in the final stages of the program were directed toward demonstrating the Mod II ASE in the USPS van rather than toward completing the engine performance and technology development and achieving the predicted fuel economy gains.

A high coolant temperature with the Mod II ASE in the USPS van is believed to result from a restricted airflow to the radiator. It should be noted, the USPS would not permit the vehicle appearance to be modified: all cooling air had to enter through the vehicle's normal inlet grill. This was adequate for the spark ignition engine but not for a Stirling, which rejects significantly more waste heat through a larger radiator.

3.1.3.3 Emissions. - Emissions results (included in appendix D) are very limited. Basically, these data indicate that the current level of Federal standards can be met without the use of a catalytic converter. However, no emissions durability data have been obtained, and no effort has been made to determine the minimum emissions that Stirling combustion systems might achieve. Review of the limited emissions data shows good emission results for the Mod I engine in the D-150 pickup truck as tested by Southwest Research Institute (ref. 9, 10) and by the State of Colorado (ref. 11). However, the Mod II ASE installed in the USPS LLV displayed emissions significantly different from those obtained in the Mod I ASE test in the D-150. It would appear either that there was something wrong with the Mod II ASE combustion system as tested in the USPS LLV or that the Mod II ASE combustor is an inherently higher emissions combustor. Several factors could be contributing to these differences. Most significantly, the Mod II combustor is physically smaller than the Mod I so that air/fuel residence time in the combustor is shorter and combustion may not be as complete, thereby resulting in higher emissions. Also the Mod II ASE operated at a higher heater head temperature (820 °C), which may raise combustion temperatures. The higher temperature tends to increase oxides of nitrogen (NO_x) emissions.

3.1.3.4 **Manufacturing costs.** - Expected manufacturing costs are, of course, a major factor in considering any new alternative engine and are a frequently cited concern by industry in regard to Stirling. An extensive cost study of the Mod II ASE was carried out by Deere & Co. with MTI, as part of the ASE program. In this effort Deere conducted in-depth value analysis and value engineering (VA/VE) to improve manufacturability and lower costs. Introduction of a number of the VA/VE design modifications aimed at cost reduction, however, could also affect engine performance and therefore would have to be verified in engine testing. This effort was never fully completed and Deere ultimately withdrew from the program. Deere had concluded however, that the engine could be built for a competitive cost for niche markets (e.g., light-duty truck applications) at production rates of about 15,000 units per year.

3.1.3.5 **Other significant results.** - Other significant results included satisfactory operation on a variety of fuels. The Mod I ASE D-150 pickup truck operated well on unleaded gasoline and JP-4 fuels interchangeably. The Mod II ASE USPS van was operated on unleaded gasoline and diesel fuel. To switch from gasoline to diesel only required pressing a button to adjust the control system to the differing fuel characteristics (particularly the air/fuel ratio). This ready capability for operation on a variety of liquid fuels is due to the external combustion system, which operates with low pressure, and continuous combustion and requires no particular octane or cetane rating.

During the NASA project Lewis made a substantial effort to develop and identify low-cost, nonstrategic, high-temperature materials, with low hydrogen permeability, that would allow the Mod II ASE to operate at 820 °C heater head temperatures. This effort was successful. A heater tube material, CG-27, and a heater head casting material, 4G-A1, were identified that met these basic requirements. It is important to note however, that NASA Lewis only addressed material costs, not fabrication costs (machining, brazing, etc.). It should also be noted that limited niche market production (10,000/yr) could drive materials costs up, particularly if there is no other significant use for these materials. A more detailed discussion of the Lewis materials effort is contained in appendix E.

When tested for infrared (IR) signature at the U.S. Army Tank Automotive Command, the Mod I ASE in the D-150 Dodge pickup truck "exhibited much lower IR signature levels during testing," than a conventional V-8 Dodge D-150. The Army indicated that "the low IR signature of the engine would be ideal for applications in light wheeled vehicles for transport of forward observers." The applicability of reduced IR signatures to auxiliary power units and heavy combat vehicles was also suggested (ref. 12). However, the Army did not pursue Stirling engine technology.

The DOE ASE program can claim success in the good drivability demonstrated in the Air Force van, the Air Force D-150 pickup truck, and the USPS delivery van, although it experienced shortfalls in emissions reduction and fuel economy.

3.1.3.6 Industry concerns. - At the start of the DOE ASE program industry had indicated a number of specific concerns regarding Stirling and the automobile application. Table III presents these concerns and indicates progress toward resolving them. Cost and vehicle testing were discussed previously.

TABLE III - INDUSTRY-DEFINED TECHNICAL CONCERNS AND PROGRESS

Industry concern	Goal	Progress	Comments
Excessive hydrogen leakage	Recharge in 6 months	From one day in Air Force van to 2 weeks in USPS van	Still far from acceptable for commercial use.
Piston ring wear and piston rod seals	3,500 hours	Mod I - 2,000-hour dynamometer endurance test Mod I - 1,429 hours in Air Force van Mod I - 1,204 hours in pickup truck Mod II - 517 hours in USPS van	Promising results with limited statistical base.
Heat rejection	50 °C	Acceptable in Spirit, Air Force van, and pickup truck. Marginal in USPS van (heat rejection and performance modifications to radiator inlet required).	Acceptable in some vehicles but could affect vehicle appearance in some vehicles.
System cost	Competitive with equivalent powerplants	Judged acceptable by Deere when compared with low-volume industrial diesel engines. Heater head costs still a concern.	Selected heater head materials may be too expensive at low production rates if the material application is only for Stirling.
Vehicle operation		ITEP and TU programs showed good drivability.	No longer a concern

3.2 STATUS OF ANOTHER STIRLING KINEMATIC CONFIGURATION

Stirling engines are being considered for a variety of stationary and mobile applications ranging from an 8-watt heart-assist pump for medical use in humans up to megawatt size for submarine applications. As previously noted, Stirling engines fall into two basic types, kinematic and free-piston. Kinematic engines use a mechanical device such as a crank or a swashplate to convert reciprocating motion from a piston (or pistons) to rotary motion to power a device such as a generator, a pump, or a vehicle. Free-piston Stirling engines, on the other hand, incorporate an output device such as an electric generator, a hydraulic pump, or a compressor directly into the engine; thus converting reciprocating piston motion directly to useful output power. The following paragraph discusses the status of another kinematic Stirling configuration that may contribute to the application of Stirling engines to the automobile.

The kinematic Stirling engine known as the STM4-120 is being developed by Stirling Thermal Motors, Inc. (STM), Ann Arbor, Michigan. The STM4-120 is a four-cylinder, double-acting engine featuring a variable-stroke power control (see appendix F). The engine was optimized to deliver 25 kilowatts (33 horsepower) at 1,800 rpm, with a maximum power of 40 kilowatts (53 horsepower) at 3,400 rpm. It was originally designed for nonautomotive uses (i.e., generator sets, solar applications, and cogeneration applications) and employed a heat pipe-heater head. During 1989, STM designed a direct-fired heater head for the STM4-120 that they believe would be applicable to city buses and small commuter vehicles. STM has built and done limited testing on four of the heat pipe engines, accumulating about 300 hours of operation. The maximum output delivered to date is about 23 kilowatts (31 horsepower). No efficiency data, however, have been gathered for power levels above 12 kilowatts (16 horsepower). The direct-fired version of the engine has not yet been tested. The STM engines are in the early stages of development and no engine/vehicle system integration studies are under way.

3.3 COMMERCIALIZATION READINESS AND TECHNOLOGY STATUS

3.3.1 Commercialization Readiness

From the results presented so far, it is clear that the Mod II ASE has not yet demonstrated the key fuel economy and emission goals of the program. Therefore, it is the opinion of the Government study participants that the subject (Mod II ASE) automotive Stirling engine is not yet ready for a commercial demonstration. To be considered ready for a Government/industry-supported commercial demonstration, a proof-of-concept engine must demonstrate that key criteria critical to the engine's commercial success and its contributing to long-term national energy and environmental goals can be achieved. Key criteria that need to be met in a proof-of-concept evaluation are shown in table IV.

The ability to meet emissions and fuel economy standards should first be demonstrated with a proof-of-concept engine installed either in a vehicle of interest for a niche market (e.g., a light-duty truck) or in a passenger car.

Manufacturability and expected costs should be determined by the manufacturer in an in-depth study of the design and of any modifications required to make it manufacturable at acceptable costs. The proof-of-concept engine need not itself meet the manufacturability requirement, provided that the manufacturer shows how the commercial demonstration version of the engine will comply. Reasonable evidence of durability, especially with regard to emissions, should be demonstrated with the proof-of-concept engine to reduce risk in the commercial demonstration. There is evidence that an ASE can meet the original Federal emissions goals (see pg. 9) of the recently completed 12-year, $130 million program. However, that program did not provide compelling evidence that future emissions or fuel economy goals could ever be met by the

TABLE IV - KEY CRITERIA TO BE DEMONSTRATED WITH PROOF-OF-CONCEPT ENGINE

National goals	Industry goals
Environmental: Emissions that meet projected standards[a] Energy conservation: Fuel economy that meets projected requirements[a] Ability to use a variety of alternative fuels	Manufacturability Cost competitiveness (first cost and maintenance) operating costs such as fuel and maintenance) Ability to meet future emissions standards Ability to use alternative fuels Ability to meet fuel economy requirements

[a] Ten to twenty years in the future.

Mod II ASE. The program has suggested that manufacturability and durability goals can be met, but that has not been fully proven.

The commercial demonstration itself must then be conducted with a prototype engine that incorporates and verifies the design changes required to achieve manufacturability at acceptable costs. Before the actual commercial demonstration can take place, three or four prototype engines should be built and tested thoroughly to verify that the basic fuel economy, emissions, durability, and performance goals are being met. Finally, the number of engines to be built in the prototype demonstration (40 to 250) would depend on the specific market applications being considered and upon the judgment of the entire commercialization team (i.e., the engine manufacturer, commercial and Government users, and the Government agencies involved).

3.3.2 Technology Status

No significant technology barriers to the Stirling engine exist when it is examined in light of current standards. However, Stirling needs to be assessed against environmental and energy need standards expected to exist in the future when the engine might see its first years of commercial production. Emissions standards and fuel economy requirements can be expected to change over the next decade or so as conventional engines continue to improve and as emissions standards are modified to meet changing environmental needs.

The primary technology issue at this time is whether or not the Stirling engine (either the kinematic or free-piston configuration) can meet the anticipated emissions standards, say 10 to 20 years in the future. The Stirling apparently can meet the current level of Federal standards although the emissions durability of the engine has not been verified. Further, no attempt has been made in the DOE ASE program to determine the minimum achievable emissions. Thus, Stirling's ability to meet the emissions standards anticipated in the future is unknown.

3.3.3 Emissions and Fuel Economy

Current and proposed automotive emissions and corporate average fuel economy (CAFE) standards are traditionally examined separately rather than together as associated standards that influence each other. Current interest in our overall environment has caused an ongoing evaluation by the Government and environmental groups that has resulted in the automotive industry making conventional engines more efficient and cleaner. As a consequence, the baselines in both emissions and CAFE standards and regulations are changing. Also, more stringent emissions regulations are being proposed for all powerplants including truck (light duty and heavy duty) and off-highway and stationary applications. It would be reasonable to expect that in the future all light trucks, vans, and pickups would have to adhere to the same stringent emissions standards as the passenger car. Furthermore, stricter regulations are being created for unique geographical locations where special conditions exist, such as the ozone formation within confined air basins in California and high carbon monoxide (CO) levels in areas that combine cold weather and high altitude such as Denver, Colorado. Also, additional improvements in fuel economy will reduce emissions of carbon dioxide (CO_2), the gas that may cause global warming.

Any alternative powerplant proposed for a demonstration program must be designed and evaluated for the emissions and fuel economy standards of the future (not the phase-in procedure currently used for today's production engines) and for the time when it would be introduced into the marketplace. The fuel economy and emissions goals for an alternative powerplant proposed for demonstration today should certainly be directed to the year 2000 and beyond.

4.0 COMMERCIALIZATION ENVIRONMENT

In carrying out this study visits were made to two automobile companies - Ford Motor Company and General Motors Research Laboratories - and several engine companies - Deere & Company, Cummins Engine Company, Hercules Engine Incorporated, and Kennedy Engine Company. An identical list of questions was submitted to each company before the visit to serve as a basis for discussion, and NASA requested that each company provide written responses. The questions and the written responses received are included as appendix G.

4.1 INDUSTRY RESPONSES

4.1.1 Automobile Companies

The responses from **Ford Motor Company, Dearborn, Michigan, and General Motors Research Laboratories, Warren, Michigan,** were quite similar, reflecting both the same attitudes and the same concerns and issues with Stirling. Both recognized the quiet operation and multifuel capability of Stirling engines. GM also acknowledged the good torque curve for Stirling but feels that this is a minor advantage readily compensated for by the transmission in spark-ignition-powered vehicles. Issues cited by both included the following:

1. Fuel economy - Ford believes, on the basis of the ASE test data, that Stirling engine fuel economy is no better than that of the best current spark ignition engines and questions whether it can ever be good enough to justify the investment required for such a new technology. GM concurs based on their evaluation of the 1984 Stirling-powered Spirit vehicle test data, which exhibited poorer fuel economy than the spark-ignition-engine-powered Spirit.

2. Emissions - Both companies strongly question the potential for Stirling to reach the 0.2-g/mile NO_x emission that has been proposed as a standard in the year 2004, indicating that it may be well beyond the capability of the continuous-combustion technology used in Stirling engines.

3. Packaging - Both Ford and GM indicated that packaging the Stirling engine, particularly in view of the larger radiator required, might be difficult, particularly with the low hood lines of modern aerodynamic vehicles.

4. Hydrogen containment - Both companies indicated that the current hydrogen recharge interval of approximately 2 weeks was unacceptable for the automobile application. General Motors indicated that hydrogen recharges should be no more frequent than current oil changes.

5. Costs - Both companies expressed concerns over production costs, particularly the cost of the heater head with its high-temperature tubing.

In addition to these issues, General Motors cited concern over the relatively long cold-start times required by Stirling as being unacceptable to the driving public. They also cited the relatively large amount of power required to drive the cooling fan should it be required in extreme operating conditions, such as going up a grade, when the fan might have to cycle on to maintain radiator temperatures. (The Chrysler Corporation was not part of this study because of previous statements by Chrysler that they did not get involved in such advanced technology activities and would instead follow the lead of Ford and GM in pursuing anything as major as a new engine technology.) Neither Ford nor GM chose to respond to our request to define an appropriate demonstration program.

4.1.2 Engine Companies

4.1.2.1 Deere & Company. - Deere & Company, Moline, Illinois, submitted a written response including point-by-point answers to the 10 questions that we asked. To summarize briefly our discussions and Deere's written response: Deere had been extremely interested in Stirling and was the key participant (the potential manufacturer) in the NASA TU effort and acted as a subcontractor in conducting the value analysis and value engineering study. As a result of that participation they presented testimony to the Congress explaining in detail what would be needed to commercialize the engine - mainly to conduct a commercial-based field test of a statistically significant number of prototype engines in the hands of potential buyers. They estimated that a total of $85 million would be required for the project, with $20 million to be provided by the Government primarily to support the commercial demonstration program. When Federal support was not forthcoming, Deere dropped the project.

4.1.2.2 Cummins Engine Company. - The Cummins Engine Company, Columbus, Indiana, is unique in the United States as the only major U.S. engine manufacturer pursuing Stirling engines for commercial application. Cummins is currently conducting two Stirling engine programs for solar power application. In both cases these are free-piston Stirling engines with electric power output. The first of these is a 5-kilowatt solar-powered, free-piston Stirling conversion system. This activity is privately funded by the Cummins Engine Company. The solar-dish Stirling system has already completed initial proof-of-concept solar-powered tests. The second program is for a 25-kilowatt solar-powered free-piston Stirling engine. This is a cost-shared program funded by DOE and Cummins Engine Company through NASA Lewis serving as the project manager. This DOE/NASA program is currently in the preliminary design stage; neither engine is directly applicable for automotive use. The Cummin's response to our questions must be reviewed in light of their free-piston Stirling engine activities. Highlights of their response follow: Fewer total parts and fewer moving parts along with the reduction or elimination of oil changes leads to the potential for low maintenance, longer life, and increased service intervals with free-piston Stirling engines. Free-piston Stirling technology, however, is in its infancy and requires substantial development. Among key disadvantages are that the free-piston is an infant technology, that Stirling engines require substantially larger waste heat exchangers than conventional engines, and that production costs at this stage are essentially unknown.

4.1.2.3 Hercules Engine Incorporated. - MTI has stated that Hercules Engine Inc., Canton, Ohio, would be their engine manufacturer in their proposed

Stirling commercialization efforts. In our discussions with Hercules they indicated that they were prepared to produce the Stirling engine but they would provide no Hercules funds to redesign the engine for production and manufacture. Hercules assessed the kinematic drive system of the Mod II ASE as conventional but was concerned with tight tolerances and unconventional components in the top portion of the engine. Hercules credited the Stirling with having a huge advantage in being "able to burn anything." They believe any new technology engine must either be cheaper, much more fuel efficient, or have much lower emissions. Hercules sees the need for a $4 to $5 million effort to redesign the Mod II ASE for production and manufacture, followed by a $10 to $15 million cost for tooling to produce 30 to 40 thousand engines per year. Hercules is concerned that the Stirling may be too costly since industrial engines sell at $1,200 to $1,300. Hercules gave a strong endorsement to natural-gas spark ignition engines, which it believes will eventually replace diesel engines in heavy-duty applications. No written response has been received from Hercules at this time.

4.1.2.4 Kennedy Engine Company. - Kennedy Engine Company, Biloxi, Mississippi, expressed a very strong interest in Stirling engines. They believe that there may be significant advantages in emissions, multifuel capability, and oil disposal, since oil changes can be reduced or eliminated. Their primary concern was their inability to obtain a Mod II ASE from MTI for evaluation. They have identified several niche markets for stationary applications that they believe Stirling can fill but suggested that more detailed marketing studies are needed. They contemplate initial Stirling applications for a 125- to 150-kilowatt Stirling engine in generator sets, cogeneration, heat recovery, marine uses, agriculture, and irrigation. At this time the Kennedy Engine Company is an engine remanufacturer, not a manufacturer. Nonetheless, they believe that they could manufacture engines by purchasing parts from suppliers and assembling and testing the engines themselves.

4.1.3 Gas Research Institute

The Gas Research Institute (GRI), Chicago, Illinois, has been supporting the development of stationary (nonautomotive) natural-gas-fired Stirling engines (with some DOE funding) since 1980 in recognition of Stirling's potential for lower emissions and less maintenance than conventional engines. They have invested over $25 million to develop a variety of stationary, gas-fired kinematic and free-piston Stirling engines. Attempts at commercialization have been unsuccessful. They point out the difficulty for Stirling to compete in low-production stationary markets with conventional engines being produced on a mass production basis. However, they see the long-term potential for the eventual commercial success of stationary Stirling. Thus, GRI plans to continue funding Stirling, although at a lower level, in order to assess worldwide Stirling development and to pursue a technology base program aimed at solving the technical problems that hinder commercialization.

4.2 COMMERCIAL DEMONSTRATION NEEDS

4.2.1 Demonstration Goals

The industry has suggested that the primary goal of a commercial demonstration would be to provide sufficient information for engine manufacturers and users to make an informed investment decision on proceeding to initial production. Specific objectives of a demonstration would include

1. Determine in a real user environment if the alternative engine meets the basic goals of performance, life, reliability, durability, emissions, and fuel economy.

2. Determine the advantages and disadvantages of the Stirling engine relative to the standard engine for that application.

3. Identify and resolve any new problems revealed in the demonstration.

4. Determine the degree of user acceptance of the Stirling engine in that application.

4.2.2 Definition of Commercial Demonstration

Both automobile companies interviewed (Ford and General Motors) declined to respond to our request for input in this area. Written inputs were received from Cummins, Kennedy, GRI, and Deere, as well as several Government agencies. They state that about 40 to 250 engines would need to be manufactured and installed in vehicles and evaluated in "real world" environments. Additional engines would be needed for life and durability testing and continued component and subsystem performance development. Such a demonstration effort must be carried out in a relatively controlled environment with trained, dedicated personnel to carry out the maintenance activities. The following paragraph from the DOE Electric and Hybrid Propulsion Division's letter (see appendix H for agency responses) distinguishes between a market demonstration, as was carried out in the electric vehicle program, and a technology demonstration as has been suggested for Stirling.

> It is important to distinguish that the electric vehicle demonstration was a market demonstration. That is, its goal was to effectively bootstrap an entire industry into existence. In order to achieve that goal, it included all phases of a prototype industry, including manufacturing, marketing, sales, and service. The goal also dictated a fairly large demonstration and well over 1,000 vehicles were involved. By contrast, for the Stirling engine, a more modest technology demonstration may be more appropriate. A technology demonstration involves about 50 to 100 vehicles. These vehicles are usually identical and

concentrated in a small number of fleets, so that maintenance activities can be conducted by properly trained full time personnel. The vehicles can be assigned to different users to evaluate user reactions. The technology demonstration concentrates on an evaluation of vehicle and subsystem performance, reliability, and cost in a semi-controlled environment. It does not attempt to create a prototype industry or to simulate actual free market conditions. The vehicles are assigned to trained personnel and subjected to periodic service and maintenance procedures to assure reliable operation.

4.3 BUSINESS CONSIDERATIONS

4.3.1 Risk Reduction

Industry comments suggest the major overriding business consideration required to put an alternative engine such as Stirling into production is the very high risk involved. Factors contributing to this high risk include

1. Ability to meet performance goals
2. In-service life, reliability, and durability
3. User acceptance
4. New mass production manufacturing requirements
5. Production costs
6. Maintenance costs
7. Warranty liabilities

This very high risk combined with the very high cost of tooling up for mass production of an alternative engine make it highly unlikely that such a new engine would ever be introduced directly into the high-volume automobile production market. Instead the engine should first be commercialized in limited niche markets in small quantities (of the order of a few thousand per year) where initial tooling costs should be more reasonable. Even then, in these niche markets the risks could still be too high for an engine manufacturer to commit to full production.

4.3.2 Government and Industry Cost Sharing

In addressing the questions of funding and Government and industry cost sharing for a commercial demonstration, it seems appropriate to assess the potential benefits of any alternative engine technology and to whom these benefits would accrue. The DOE ASE program has been aimed at two basic goals - fuel economy and emissions. These are national goals whose benefits would accrue to the general public. The primary corporate benefit is an improved ability to meet future emissions and fuel economy standards.

If a new alternative engine technology shows sufficient potential for meeting key national goals, it might be appropriate that Government funding be provided to help reduce the risk sufficiently so that a manufacturer could arrive at an informed decision and proceed to production. At the same time industry's cost share should reflect a reasonable balance of risk, corporate commitment, and potential corporate benefits (profits and ability to maintain market share in the face of more stringent regulations).

5.0 FEDERAL PARTICIPATION AND SPONSORSHIP

Although all the involved Government agencies were cooperative in contributing to this report, none have indicated the desire to participate in long-term sponsorship of a Mod II ASE engine commercialization effort. (See individual agency responses in appendix H.) DOE's Office of Transportation Systems states that the ASE technology and the information "are available for industry's use in any further commercial demonstration activities" and "commercialization efforts focused on demonstrations with potential customers . . . should be supported solely by the industry."

6.0 FINDINGS

The following findings are offered regarding the Mod II ASE developed under DOE sponsorship:

1. **The Mod II ASE has not achieved a level of performance or value that would interest any Federal agencies or engine/automobile manufacturers in a commercial demonstration program.** Neither the Mod II ASE development effort by the engine developer nor the proof-of-concept evaluation conducted with potential users achieved all of their goals, although the proposed engine designs were completed. The fuel economy goals of the program were not met. Although the emissions reduction potential appears to have some promise, it has not been fully determined, nor has the emissions durability of the Mod II ASE been verified. Although the Mod II ASE meets the current level of Federal emissions standards, any new alternative engine such as Stirling must be directed to meet the Federal standard anticipated when the engine will be introduced into the marketplace.

2. **Introducing any new alternative engine directly into the automobile in the near term is highly unlikely because of the large capital investment, the high risk, and the difficulty of predicting manufacturing costs.** Instead, initial application in a niche market at relatively low production quantities may build the confidence and experience needed to support a later mass production decision.

3. **Advancing the program beyond the proof-of-concept phase must involve the engine and vehicle manufacturer.** The Mod II ASE was intended to offer improved manufacturability and lower cost, the engine and vehicle manufacturers will need to decide what further improvements are necessary for initial market entry.

4. **Commercial demonstration plans must be defined primarily by the engine manufacturer and developer and the user organizations** (both private and Government) and could involve anywhere from 40 to 250 engines.

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STIRLING COMMERCIALIZATION STUDY

FINAL REPORT

Volume II

by
National Aeronautics and Space Administration
Washington D.C. 20546

and

National Aeronautics and Space Administration
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Volume II of II

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APPENDIX A

LANGUAGE FROM HOUSE REPORT 101-226
ACCOMPANYING HR 1759,
THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MULTIYEAR AUTHORIZATION ACT OF 1989.

Committee View
Management of the Stirling Engine Program

The Stirling engine may eventually contribute to a long-term solution to the nation's emission problems and represents a strategic alternative for pollution abatement. Research and development in Stirling technology suggest the logical next step for the Stirling is a commercial demonstration of the engine which would place into the hands of end-users multiple Stirling units for field tests. Supporters of the Stirling engine have proposed a government and industry cost-sharing demonstration program.

For the last decade, the federal government has funded a Stirling engine research, development, and demonstration program, with DOE providing $130 million and NASA only $0.9 million. Because of its expertise in combustion technology, NASA managed the Stirling program on behalf of DOE. There is a strong consensus that the automotive Stirling engine has matured beyond the R&D stage. Therefore, DOE has decided to terminate its Stirling engine R&D program and has not requested any funding for it in FY 1990.

For the last 4 years, NASA has funded a $900,000, 3-vehicle demonstration program. It has been suggested that full sponsorship of the Stirling engine program be transferred from DOE to NASA. The Committee is uncertain whether transferring agency sponsorship would be in the best interests of Stirling engine development and commercialization.

To determine the optimal long-term sponsor for the Stirling engine, the Committee directs NASA to participate in an interagency study including the Department of Energy, the EPA, and the Air Force, in consultation with other interested agencies, to evaluate potential sponsorship of such a program. The study should include the optimal size and scope of the demonstration fleet, a determination of the private sector contribution, and a mechanism for securing such funds. The Committee encourages NASA to consult with the private sector in developing the study plan. The study should be submitted to the Congress by February 1, 1990.

APPENDIX B

DEFINITIONS

Stirling engine - Any closed-cycle, externally heated, hot-gas engine employing regenerative heating. Theoretically, the Stirling engine cycle provides the maximum cycle efficiency achievable in an engine. (For an explanation of the basic Stirling cycle please, see appendix F.)

Kinematic Stirling engine - Any Stirling engine employing a mechanical device, such as a crank or swashplate, to convert reciprocating power from a piston to rotary shaft power to drive a device such as an electric generator pump or a vehicle.

Free-piston Stirling - Any Stirling engine in which a power output device such as an electric generator, a hydraulic pump, or a compressor is incorporated directly into the engine. No mechanical device is employed to convert the reciprocating piston power to rotary shaft power.

Mod I ASE - The first-generation, experimental, kinematic Stirling engine designed and built in the DOE Automotive Stirling Engine (ASE) Program.

Mod II ASE - The second-generation, proof-of-concept, kinematic Stirling engine designed and built in the DOE ASE program and intended to demonstrate achievement of the DOE program goals.

APPENDIX C

DEPARTMENT OF ENERGY
AUTOMOTIVE STIRLING ENGINE PROGRAM
CHRONOLOGY

February 1978	Public Law 95-238, Title III (The Automotive Stirling Engine Program evolved from this legislation.)
March 1978	Contract DEN3-32 awarded to MTI.
May 1980	Final Mod I ASE design review conducted.
January 1981	First Mod I ASE hot engine test performed.
April 1981	First Mod I ASE Stirling engine system test performed.
August 1981	Mod I ASE engine is fully characterized.
May 1982	First Mod I ASE is installed in vehicle.
July 1982	First USA-built Mod I ASE begins test.
April 1983	First upgraded Mod I ASE begins test.
May 1983	Reference engine radically redesigned and Mod II ASE design begun.
May 1984	Mod I ASE in Spirit vehicle tested by GM Research Laboratories as part of ITEP.
September/ October 1984	Mod I ASE evaluated by Deere as part of ITEP.
April 1985	Mod II ASE basic engine design review conducted.
August 1985	Mod II ASE engine system design review conducted.
September 1986	Mod I ASE in Air Force multistop van delivered to Langley AFB for phase I of NASA TU demonstration. Completed August 1987.
July 1986	Mod II ASE begins testing.
September 1987	Mod I ASE in Air Force D-150 pickup truck delivered to Langley AFB for phase II of NASA TU demonstration. Completed August 1988.
February 1988	First Mod II ASE is fully characterized.
May 1988	Mod II ASE installation in USPS LLV completed.
September 1989	Mod II ASE in USPS LLV is delivered to Merrifield, Virginia, for phase III of NASA TU demonstration. Completed December 1989.
December 1989	Contract DEN 3-32 is concluded.

APPENDIX D

EMISSIONS AND FUEL ECONOMY

Current interest in our overall environment has caused an ongoing evaluation of automotive emissions and fuel economy standards by the Government and environmental groups that has resulted in the automotive industry making conventional engines cleaner and more efficient. As a consequence, the baselines in both emissions and fuel economy standards and regulations are changing. Also, more stringent emissions regulations are being proposed for all powerplants including truck (light duty and heavy duty) and off-highway and stationary applications. It would be reasonable to expect that in the future all light trucks, vans and pickups would have to adhere to the same stringent emission standards similar to those imposed for passenger cars. Further, stricter regulations are being created for unique geographical locations where special conditions exist, such as the ozone formation (ref. D-1) within confined air basins such as California and high carbon monoxide (CO) levels (ref. D-2) in areas that combine cold weather and high altitude such as Denver, Colorado. Also, additional improvements in fuel economy will reduce emissions of carbon dioxide (CO_2), a gas which may cause global warming. It should be noted that, current and proposed automotive emissions and corporate average fuel economy (CAFE) standards are traditionally examined separately rather than together as associated standards that influence each other.

Current automotive exhaust emissions standards established by the Federal Government and the State of California are listed in table V. The Federal standard for unburned hydrocarbons is based on the total hydrocarbon content of the exhaust; the California standard includes all hydrocarbon constituents except methane. The California standards for nonmethane HC and CO will be lowered, as shown, in 1993. The Federal standard also includes a limit of 0.6 g/mile on exhaust particulates. The corresponding exhaust particulate limit in California is 0.08 g/mile. Three different proposals for Federal automotive emissions standards are presented in table VI (from ref. D-3).

A significant amount of research and development funds are being spent by the automotive industry and engine manufacturers to meet the current and future EPA

TABLE V - CURRENT AUTOMOTIVE EMISSIONS STANDARDS

Emissions standard	Total HC	Nonmethane HC	CO	NO_x
	Gaseous exhaust emissions, g/mile			
Federal	0.41	--	3.4	1.0
California	--	0.39	7.0	0.4
	--	[a]0.25	[a]3.4	

[a] Nonmethane HC and CO standards would be reduced to these limits in 1993.

and California Air Resources Board (CARB) regulated emissions standards (ref. D-4) and Federal CAFE requirements (ref. D-5). Most of these resources are directed at changes to conventional powerplants that are currently in production. More stringent emissions and fuel economy standards are being phased in to allow time for the industry to modify and verify the conventional engine. The lowest proposed Federal exhaust emissions levels for the gasoline-fueled passenger car are 1.7 g/mile for CO, 0.2 g/mile for NO_x, 0.125 g/mile for total hydrocarbons, and 0.08 g/mile for particulates. In addition to tailpipe emissions, requirements are now being proposed for evaporative, refueling, and running loss emissions (ref. D-3).

Ultimately, any alternative powerplant proposed for a demonstration program must be designed and evaluated for the emissions and fuel economy standards of the future (not the phase-in procedure currently used for today's production engines) and for the time when it would be introduced into the marketplace. The emissions and fuel economy goals for an alternative powerplant proposed for demonstration today should certainly be directed to the year 2000 and beyond.

TABLE VI. - PROPOSED FEDERAL AUTOMOTIVE EMISSIONS STANDARDS

[From ref. D-3.]

	Useful life, years/thousand miles	Current standards	Recommended by Administration	Reported by House subcommittee		Reported by Senate subcommittee	
				Phase 1	Phase 2 (2004)[b]	Phase 1	Phase 2 (2003)
Emissions, g/mile							
Nonmethane HC	5/50	[a]0.36	0.25	0.25	---	---	---
	7/75	---	---	.31	---	---	---
	10/100	---	---	---	0.125	0.25	---
Total HC	5/50	0.41	0.41	---	---	---	---
	7/75	---	---	---	---	---	---
	10/100	---	---	---	---	0.31	0.125
CO	5/50	3.4	3.4	3.4	---	---	---
	7/75	---	---	4.2	---	---	---
	10/100	---	---	---	1.7	3.4	1.7
NO_x	5/50	1.0	0.7	0.4	---	---	---
	10/100	---	---	---	0.2	0.4	0.2
Evaporative emissions		Same control	Better control	Better control		Better control	
Running losses		No control	Control	Control		Control	
Refueling emissions		No Federal control	Stage 2	Stage 2; onboard if safe		Stage 2 + onboard	
I/M		Basic	Enhanced	Enhanced		Enhanced	
RVP (psi)		10.5	9.0	9.0		9.0	
Emission Warranties		5/50 for defects, all parts	Same as current	Same as current		Extended to 8/80 for catalyst and electronic control unit; reduced to 2/24 for all other parts	
Emission system diagnostics		No requirement intent to adopt something	Authority and something	EPA must adopt something		EPA must adopt	

[a] Rough equivalent to actual total HC standard, for comparison with proposals.

[b] House Subcommittee phase 2 standards are subject to EPA study and revision, not to exceed phase 1 standards.

ASE EMISSIONS AND FUEL ECONOMY

The emissions and fuel economy data are presented for the Mod I ASE powered Dodge D-150 pickup truck shown in table VII and the Mod II ASE powered Grumman Long Life Vehicle (LLV) shown in table VIII. All the data presented were for vehicles evaluated at certified facilities and driven on the EPA urban/highway driving cycle.

A comparison is made in table VII for the 1987 Dodge D-150 pickup truck powered by the Mod I ASE (80 horsepower) and a by conventional spark-ignition engine

TABLE VII. - COMPARISON OF STIRLING (MOD I ASE) AND SPARK IGNITION (3.7 LITER) ENGINES IN THE D-150 PICKUP TRUCK FOR EXHAUST EMISSIONS AND FUEL ECONOMY.

Date of Evaluation Vehicle Description Engine Description	Emissions, g/mile			Mileage, miles/gal		
	HC	CO	NO_x	Urban	Highway	Combined
April, 1988 '87 D-150 - 4000 lb Mod I ASE	0.33	3.18	1.14	16.8	26.4	20.1
October, 1988 '87 D-150 - 4000 lb Mod I ASE	0.14	0.70	0.77	18.0	27.2	21.2
November, 1989 '87 D-150 - 4000 lb Mod I ASE	0.23	0.98	0.67	16.7	25.2	19.7
'87 EPA Data '87 D-150 SI, 3.7 liter (95 hp)	0.31	2.30	1.36	16.8	21.8	18.7
Current Federal Emissions Standards LDT - Class 2	0.8	10.0	1.7			
Current Federal Emissions Standards Automotive	0.41	3.4	1.0			

(3.7-liter Slant six, 95 horsepower). Also, shown are the current emission standards for the light duty truck (Class 2) and the current Federal standards for the automotive application. The data base for the experimental Mod I ASE is limited, although it appears to be representative of the Mod I ASE external combustion system. The Mod I ASE data meet the current Federal emission standards for the light duty truck (Class 2). It appears that the relatively poor emissions performance of the conventional Dodge pickup truck engine is due in part to the looser standards for LDT's, since the tighter automobile standards can easily be met by a vehicle of similar weight powered by a conventional gasoline engine (LeSabre). Notwithstanding, the data show a wide range for the individual emissions - suggesting that no conclusion can be reached. Fuel economy improvements for the Mod I ASE range from 5 to 14 percent in the combined urban/highway cycle, when compared to the conventional spark-ignition engine in the D-150.

A comparison of the Grumman Long Life Vehicle (LLV), otherwise known as the USPS delivery van, powered by the Mod II ASE (nominal 73 horsepower) and a conventional spark-ignition engine (2.5 liter, 92 horsepower) is shown in table VIII. Also shown are the current Federal emission standards for the light duty truck (Class 1) and the current Federal standard for the automotive application. The Mod II ASE was designed for the automotive application to demonstrate the DOE program goals for emissions and fuel economy (see page 9). Specifically, the Mod II ASE was to be installed in a 1985 GM Celebrity, however it was never installed and no data are available.

The data base for the proof-of-concept Mod II ASE is very limited, and while it appears that the CO and HC emissions standards can be met by the Mod II ASE, the data for NO_x is marginal at best for the Mod II ASE for the current and proposed Federal emission standards for the light duty truck (Class 1). As with the Mod I ASE, the Mod II ASE shows a wide range for the individual emissions. Fuel economy improvements for the Mod II ASE fell short in the urban cycle and improved in the highway cycle, resulting in a 2 - 5 percent combined fuel economy loss when compared to the conventional spark-ignition engine (with EPA data for the 1989/1990 model years) in the Grumman LLV. However, the Mod II ASE data for

TABLE VIII. - COMPARISON OF STIRLING (MOD II ASE) AND CONVENTIONAL SPARK IGNITION ENGINES FOR EXHAUST EMISSIONS AND FUEL ECONOMY.

Date of Evaluation Vehicle Description Engine Description	Emissions, g/mile			Mileage, miles/gal		
	HC	CO	NO_x	Urban	Highway	Combined
October, 1989 Grumman LLV - 3375 lb Mod II ASE	0.11	2.18	1.09	17.9	27.9	21.3
December, 1989 Grumman LLV - 3375 lb Mod II ASE	0.165	1.6	1.54	17.6	26.6	20.7
'89/'90 EPA Data Grumman LLV - 3625 lb SI, 2.5 liter (92 hp)	0.22	6.8	0.32	20.4	23.9	21.8
'89 EPA Data '89 Celebrity- 3125 lb SI, 2.5 liter (100 hp)	0.108	0.71	0.22	26.3	39.6	31.0
'89 EPA Data '89 LeSabre - 3625 lb SI, 3.8 liter (165 hp)	0.150	1.15	0.24	20.6	35.9	25.5
Current Federal Emissions Standards LDT - Class 1	0.8	10.0	1.2			
Current Federal Emissions Standards Automotive	0.41	3.4	1.0			

December 1989 contains an anomaly (engine flameout during the test run) and may not be representative of the Mod II ASE external combustion system. It should be noted that in 1989, MTI conducted back to back "on-the-road" tests in the Albany, New York area with a Mod II ASE and a spark ignition engine installed in Grumman LLVs. According to MTI, these fuel economy tests, resulted in a 13 percent combined fuel economy gain for the Mod II ASE in the "simulated" urban/highway combined cycle when compared with the conventional spark-ignition engine.

Although it may not be totally prudent to compare exhaust emissions from production vehicles with those from experimental or developmental vehicles, comparing EPA data (ref. D-6) indicates that the MTI's ASE powered vehicles have about the same level of total hydrocarbons and CO as the spark-ignition-powered vehicles but a somewhat higher NO_x emission level. In order to provide a rough benchmark with the limited data available from vehicles powered by the Mod II ASE, EPA data from a few production automobiles are presented in table VIII.

The test data for the Mod I ASE's powered vehicles shown in table VII were obtained with gasoline. Limited test results for the D-150 pickup truck have also been obtained with oxygenated fuel blends containing 11 percent methyl tertiary butyl ether (MTBE) in gasoline (refs. D-7 and D-8). The leaning effect of oxygenated fuel blends tends to reduce carbon monoxide emissions for vehicles with spark-ignition engines operating at cold-weather and high-altitude conditions. The limited CO emissions data comparing 11 percent MTBE fuel blends with gasoline do not appear to be conclusive: for some tests there were no significant differences; other tests indicated a somewhat lower CO level when the 11 percent MTBE fuel blend was used. The Mod I ASE emissions are penalized somewhat by the need for warmup periods (70 to 80 seconds prior to cold start and 20 to 30 seconds prior to hot start) in order to reach the required heater head operating temperature. The Mod I ASE emissions data from reference D-8 were obtained with an exhaust gas recirculation (EGR) ratio of 37 percent; the EGR used for the other Mod I ASE powered vehicle tests (refs. D-7 and D-9) is not known. Increasing EGR tends to reduce NO_x without affecting other emission products. An important consideration is that the production vehicles contain catalytic converters but the Stirling-engine-powered vehicles contain no catalytic converters.

The potential to attain acceptable vehicle performance, reliability, durability, and cost with various advanced powerplants and alternative fuels while meeting future emissions standards is discussed by Amann of GMRL (ref. D-10). Advanced versions of the conventional four-stroke spark ignition engine are compared with alternative powerplants, including the two-stroke spark ignition engine, the low-heat-rejection diesel, the Stirling engine, and the gas turbine. The diesel would appear to be the least attractive candidate for a passenger car powerplant because of its low potential for achieving future emissions standards for both NO_x and particulates. The effect of higher cylinder operating temperatures in the low-heat-rejection diesel on NO_x and particulates has not been clearly identified, as yet. It is not entirely clear at this point whether any Stirling engine would have any more potential than the spark ignition engine in meeting more stringent emissions standards. However, the Stirling engine does have several characteristics that enhance its ability to control emissions. The fact that the Stirling engine uses a external-continuous combustion system simplifies the introduction of emission controls because the combustion system is isolated from its closed working cycle. Since the Stirling engine has multifuel capability, it would be amenable to the use of alternative fuels. The use of a less volatile fuel such as No. 2 diesel would have the advantage of minimizing evaporative losses from the fuel system. Finally, the addition of a catalytic reactor to the Stirling engine could further reduce hydrocarbon and carbon monoxide emissions. However, temperatures at the tailpipe of the Stirling engine may not be high enough to provide efficient combustion. Therefore, it may be necessary to position the reactor between the combustion chamber and the preheater. The use of a heated catalytic reactor as previously discussed could have potential for the Stirling engine as well as the spark ignition engine. If it were possible to operate the Stirling engine's external combustion chamber at near stoichiometric conditions to minimize the oxygen content of the exhaust, the use of a NO_x-reducing catalyst might also be explored. Operation of the combustion chamber at near stoichiometric conditions presumes the availability of adequate high-temperature materials, or cooling technology, or both to ensure the suitable durability and life of all high-temperature components.

Both the emissions and fuel economy results for the Mod I and Mod II ASEs are very limited. To date, these results are both incomplete and inconclusive. The urban fuel economy gains continue to be elusive and the fuel economy gains as determined by standard EPA urban/highway fuel economy tests continue to fall short of prediction. While it appears that the CO and HC emissions can be met by the Mod II ASE, the data for NOx is marginal at best. Further, both the Mod I ASE and Mod II ASE display a wide range of individual emissions, which suggest uncertainty. And finally, emissions from the Mod II ASE display results significantly different from the Mod I ASE, which suggest uncertainty about the understanding of external combustion systems designed for the ASE's.

These uncertainties, and the general performance of the ASE, suggest that there are considerable reservations that a demonstration of ASE vehicles today would lead to vehicles with any long term emission advantage over internal combustion engines.

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APPENDIX E

AUTOMOTIVE STIRLING ENGINE MATERIALS

The high-temperature heater head of the automotive Stirling engine (ASE) represents a severe materials challenge in terms of strength, hydrogen compatibility and permeability, oxidation resistance, and cost. As initially conceived during the late 1970's and early 1980's, the Stirling engine was to be an alternative to the internal combustion engine for automotive applications. This implied a potential production volume of up to 300,000 units per year. Prototype engines at that time used cobalt alloys as the materials for the heater head tubes, the cylinder head, and the regenerator housings. Because of the limited cobalt available in the United States, it was apparent that low-cost substitute alloys would have to be identified, characterized, and validated in actual engine tests in order to be able to mass produce competitive Stirling engines. Research programs were undertaken at NASA Lewis, Mechanical Technology Inc., and United Stirling of Sweden. In a seven-year effort, substitute alloys for the heater head of the Stirling engine were validated in rig and engine tests and shown to be equal or superior in performance to the cobalt alloys initially used in prototype engines.

The substitute alloys are all iron based, thus providing a cost advantage. The present Mod II ASE design contains approximately 25 pounds of cast material for cylinder (piston) heads and approximately 6 pounds of tubing material. The Stirling engine alloys' costs are compared in the following table:

TABLE IX - COST OF STIRLING ENGINE ALLOYS
[Based on cost of raw materials. Cobalt costs $7.25/lb.]

	Estimated cost, $/lb
Tubing alloys	
CG-27	2.20
IN-625	3.50
N-155	4.00
Cylinder head alloys	
XF-818	1.75
NASAUT 4G-A1	.61
HS-31	5.55

The proposed substitute cast tubing material, CG-27, costs essentially the same as standard stainless steels, about $2.00 per pound, and one-half as much as N-155, the cobalt-base prototype tubing material. The proposed substitute cast cylinder head material, NASAUT 4G-A1, costs $0.61 per pound versus $5.55 per pound for the cobalt-base prototype cylinder head material, HS-31. The cost of these substitute materials is expected to decrease as demand increases after a market is created.

The materials requirements for some Stirling engine components are similar to those for certain spark ignition engine components; the requirements for other components are very different. For example, the heater head materials are subjected to a severe operating environment and must contain high-pressure hydrogen in the working cycle. The mean pressure of the closed-cycle system varies between 4 and 15 MPa, and cyclic pressures may reach as high as 19 MPa. The heater head tubes operate at a nominal temperature of 820 °C; and the cylinder heads, at 775 °C. CG-27 was selected as the primary alloy for the heater tubes over other candidate materials for its creep rupture properties, oxidation resistance, low hydrogen permeability, and low cost relative to cobalt-containing superalloys.

Alloy CG-27 obtains its excellent oxidation resistance and low hydrogen permeability from the oxides of aluminum and titanium that form on both the inside and outside surfaces of the heater tubes during initial engine operation. These oxides do not reduce in the high-pressure, high-temperature hydrogen; and enough oxygen, a trace contaminant, is present to form the oxides. The trace oxygen level is achieved by doping; that is, by adding small amounts of gases such as CO_2 and CO (0.02 to 1.0 vol %) to the working-cycle gas.

The strength properties of the candidate heater head materials exceed the current design requirements of the Stirling engine: a rupture life of 3,500 hours at a temperature of 860 °C and a stress of 28 MPa. Creep rupture tests on CG-27 in air and high-pressure (15 MPa) hydrogen showed that at the design maximum heater tube temperature, CG-27 has 3,500-hour rupture stresses of 45 and 63 MPa in air and hydrogen, respectively.

Fatigue has been identified as the major failure mode in the cylinder head manifolds of engines. Growth of fatigue cracks and subsequent hydrogen leakage may lead to cylinder housing failures. The fatigue design criteria for the cylinder and regenerator housing require a safety factor of 2 in the stress range produced by the number of pressure cycles in 3,500 hours.

Therefore, it is feasible for the design fatigue stress amplitude to approach a maximum of 240 MPa at 775 °C. Presently, neither the HS-31 nor the XF-818 alloy meets the design criteria in either air or 15-MPa hydrogen. The alloy 4G-A1, with 2.5 times the resistance to fatigue strain of XF-818 and 1.3 times that of HS-31 at 800 °C, is more than adequate. Fatigue tests show that the approximate fatigue-limit stress amplitude for alloy 4G-A1 is 269 MPa. Although it had been identified that the creep-rupture life of the cast components is not their limiting design criterion, an assessment of their rupture life was necessary. Creep-rupture tests in air and high-pressure hydrogen on the cast and braze-cycled 4G-A1 alloy showed that the 775 °C, 3,500-hour, 119-MPa rupture life design criteria for the cast components are satisfied. The 4G-A1 alloy exhibited a 3,500-hour stress rupture strength in excess of 180 MPa at 775 °C.

Cost is always an important issue but, in the case of the ASE, cost becomes even more important because the ultimate objective is to design an engine that could become marketable and price competitive in the automotive industry. Therefore, all of the material selections were strongly weighted toward cost effectiveness. This has contributed to the cost of an automotive Stirling engine being projected to be competitive with the cost of comparable Otto and diesel engines based on an annual production volume of 300,000. Note, however, that in low-volume production and withour supporting production needs for other uses, material costs could still be prohibitive.

On the basis of the materials research program in support of the automotive Stirling engine it was concluded that manufacture of the engine is feasible from low-cost, iron-base alloys rather than the cobalt alloys used in prototype engines.

APPENDIX F

STIRLING ENGINES - KINEMATIC AND FREE-PISTON

A TECHNICAL DISCUSSION

INTRODUCTION

Although there are many similarities between the "kinematic" and the "free-piston" Stirling engine (FPSE), the significant differences become major discriminators when selecting an engine for a specific application. A generalized comparison between a kinematic and a free-piston Stirling engine is presented below. A more detailed discussion appears in the sections following the comparison.

The kinematic Stirling engine requires a starter motor similar to an internal combustion production automotive engine. The power output is a function of the torque and speed of a rotating shaft. The engine requires an active power output control system (either a mean pressure system or variable stroke system). The mean pressure control system includes a storage bottle, a compressor and a pressure control valve. Power output is dependent on the engine speed as well as engine pressure. The required power output can be obtained at various engine speeds and pressures. In a kinematic Stirling engine, the oil lubrication system may require maintenance. If oil system maintenance is required, it will be at long internals since the oil is never contaminated by the combustion process. Also, a dynamic seal is required. The seal is either a sliding seal taking the full engine charge pressure, as in the case of the mean pressure control, used for the MTI Mod II ASE, or a sliding seal taking the oscillatory pressure along with an additional rotary shaft seal as in the variable stroke STM engines.

The free-piston Stirling engine has no active power output control system since power output is determined by the applied load. With a constant mean pressure, the power output is a function of the piston stroke which responds to the load. A specific load therefore results in the piston stroke required to match the output power to the load. A FPSE incorporating a linear alternator, and using helium working gas can be hermetically sealed and does not require a working gas makeup system. The engine operates without an oil lubrication system that could require maintenance. Also, the engine has no starter motor. The FPSE can be started by applying an electric excitation to the linear alternator. When the excitation is at the resonant frequency of the engine, the piston and displacer will begin to oscillate. This method of start up requires only a minor addition to the system controller logic.

The following discussion gives some general background information about heat engines and Stirling engines specifically. The operation of the Stirling cycle is described along with the hardware used when operating an engine.

DECRIPTION OF STIRLING CYCLE

Stirling engines are a subset of a more general category of engines known as heat engines. The common trait that links these engines is their ability to convert thermal energy (heat) into mechanical power. The heat can be supplied from any heat source at an appropriate temperature. Each cycle operates on the potential energy that exists between a high-temperature heat source and some low-temperature heat sink. The engine will absorb heat from the heat source and convert some of the heat to mechanical energy; the remaining heat is rejected to the sink as waste heat.

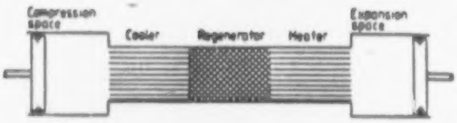
The category of heat engines includes, in addition to the Stirling cycle, the Brayton cycle as used in a gas turbine engine and the Rankine cycle as used in a steam engine. A fourth cycle, (which exists only on paper), is the Carnot cycle. The Carnot cycle represents an ideal cycle with the highest possible theoretical efficiency that can be obtained. Often the efficiency of an engine is expressed in terms of what percentage of the Carnot efficiency it has been able to obtain. Of the heat engine cycles, the Stirling cycle can obtain the highest percentage of Carnot efficiency.

The Stirling cycle is a closed cycle in which a gas known as the working fluid is shuttled back and forth between a hot region of the engine and a cold region. The hot region is called the expansion space and the cold region is known as the compression space. These regions are connected through a system of heat exchangers known as the heater, the regenerator, and the cooler. Because the cycle is closed, the working fluid is reused as subsequent cycles continue. New working fluid is not brought into the cycle nor is any fluid exhausted during each cycle. Although early engines and some modern day engines use air as the working fluid, the more common working fluid is helium or hydrogen. The high heat transfer rate of helium and hydrogen allows high-speed engine operation, and their low viscosity reduces the losses incurred in pumping the fluid through the heat exchangers.

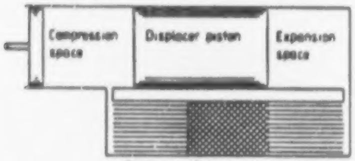
Stirling cycle engines use pistons moving in cylinders, unlike the Brayton gas turbine engine, which uses spinning turbine wheels. As a general description of the operation, the working fluid is shuttled back and forth between the hot region and the cold region of the engine. This creates a variation in the pressure of the working fluid. When the working fluid is heated, the pressure rises and pushes against the pistons. The force causes the pistons to move, increasing the volume occupied by the working fluid. During this expansion the working fluid does work on the piston. Similarly, when the fluid is cooled, the pressure is lowered and the pistons move inward, decreasing the volume and compressing the working fluid.

Two common arrangements used in Stirling engines are the alpha and the beta configurations shown in figure 19. Although the alpha and beta configurations appear different, they execute the identical thermodynamic cycle. Because the beta arrangement lends itself more easily to a description of the operation, it is described first.

There are two distinct pistons (displacer and power) in the beta engine with two distinct functions. The displacer piston shuttles the working fluid between the expansion (hot) space and the compression (cold) space, alternately heating and cooling it. The power (or working) piston motion is timed (phased) to the displacer piston motion to expand the volume when the working fluid is hot, extracting work from the cycle, and to compress the volume when the working fluid is cold. The difference between the expansion work and the compression work is the net work output of the cycle. A further description of the cycle is contained in the reference


Compression space
Cooler
Regenerator
Heater
Expansion space

(a) Alpha engine


Compression space
Displacer piston
Expansion space
Cooler
Regenerator
Heater

(b) Beta engine

Figure 14. - Common arrangements of Stirling engines: (a) alpha, (b) beta.

F-1, An Alternative Power Plant, The Stirling Engine. The same volume amplitudes and phasing can be obtained in either the alpha or beta configuration. Each engine can generate the identical thermodynamic cycle.

There are many possible ways to configure the cylinders and heat exchangers of a Stirling engine. There are also various ways to cause the desired motions of the pistons and to extract power in Stirling engines. The two broad categories are kinematic Stirling engines and free-piston Stirling engines (FPSE). Kinematic engines use mechanical devices such as cranks or swashplates to control piston motions and to convert reciprocating motion from a piston or pistons to rotary motion to power a device such as a generator, a pump, or a vehicle. Free-piston Stirling engines incorporate an output device, such as an electric generator, a hydraulic pump, or a compressor, directly into the engine. They thus convert reciprocating piston motion directly to useful output power. The FPSE pistons are generally operated as resonant systems employing gas springs, although some "free-piston" engines control displacer motion with linear electric motors or mechanical drives.

Kinematic engines and free-piston engines have some features that are similar and other features that are different. These similarities and differences are addressed in a following section.

COMMON FEATURES

Whether the pistons in the engine move through the use of a kinematic linkage or resonate on gas springs, and whether the engine layout is the alpha or beta configuration, modern Stirling engines have many common features. In all these engines, heat is input to the cycle through the heater. Some of the heat is converted to work and the remaining heat is rejected as waste heat through the cooler. Typically, the heaters and coolers are tubular heat exchangers.

Located between the heater and the cooler is another heat exchanger known as the regenerator. The regenerator serves as a thermal dam, preventing a large percentage of the heat invested in the hot working fluid from being transported directly to the cooler and lost to the cycle. As the working fluid is being shuttled from the hot region of the engine to the cold region, it must pass through the heater and the cooler. If there were no regenerator, the cooler would reject sufficient waste heat to lower the working fluid temperature from the expansion space (hot) temperature to the compression space (cold) temperature. With the regenerator placed between the heater and the cooler, much of the heat that must be removed from the working fluid is transferred to and saved in the regenerator matrix. Nearly all of the heat that must be removed from the fluid is stored in the regenerator; the remaining heat is rejected to the cooling system.

Similarly, when the fluid is being shuttled from the relatively cool compression space to the expansion space, the heat stored in the regenerator is transferred back to the working fluid. The heat supplied to the working fluid from the regenerator is once again much greater than the heat supplied to the fluid via the heater tubes. The regenerator thus acts not only as a thermal dam but also as a thermal storage device that alternately absorbs heat from the working fluid and then returns it to the working fluid.

Although this principle appears at first glance to be a little obscure, it is the same phenomenon that occurs when a person breathes through a scarf on a cold winter day. Heat is first invested in the scarf when the person exhales. The warm air transfers heat to the material of the scarf, where it is stored. This stored heat is then transferred to the incoming air when the person later inhales. The net result is that the incoming air is preheated with heat from the previously exhaled air. A highly effective regenerator will transfer a large fraction of the heat required to either preheat or precool the fluid as is passes from one temperature region to another. In modern Stirling engines this device is typically a very fine, highly porous metal matrix.

Performance and operating differences exist between a kinematic and a free-piston implementation of the Stirling cycle. The various characteristics of typical kinematic and free-piston engines are described in the following sections. Since this is a comparison of typical engines, some of the statements are generally correct yet not strictly so.

FEATURES OF KINEMATIC ENGINES

The kinematic Stirling engine is characterized by the use of a mechanical linkage or a system of linkages to coordinate the movement of the pistons and to transfer power generated to the load. This is typical of the Stirling engines designed for the automotive application and early generator sets. All Stirling engines made before the late 1960's were of the kinematic configuration.

The power output of the kinematic engine is in the form of a rotating shaft. The power level is typically modulated through the use of a mean-pressure control system or a variable-stroke control system, such as a variable-angle swashplate. With either of these systems the user will notice a change in the power output in a manner similar to common internal combustion engines. The power output will be a function of the engine speed for any given throttle setting, with various throttle settings available. A change in the throttle setting will cause the engine to follow a new curve of power output versus speed.

When a mean-pressure control system is used, as in the Mod I and Mod II ASE's, a compressor, a control valve, and a storage bottle are used to vary the inventory of the working fluid in the cycle. As the mean pressure of the working fluid is increased, more molecules of gas are heated and cooled during each cycle and subsequently more heat is converted to work. When at high mean pressure the engine produces a high-pressure swing within the cycle. As less power output is required, the mean pressure of the working fluid is lowered and less heat is converted to work. A smaller pressure swing now exists. The majority of kinematic engines built to date have been of the mean-pressure control type.

When a variable-stroke control system is used, as in the STM engine, the working fluid inventory, and therefore the mean pressure of the cycle, remains fixed. The stroke of the pistons is changed. As more power output is desired, the piston stroke is increased, causing a large volume variation and a larger pressure swing. The amount of heat converted to work increases. As less power output is desired, the stroke is shortened, causing a relatively small volume variation and a smaller pressure swing. Little heat is now converted to work.

Kinematic engines use a dynamic seal to isolate the working fluid from the crankcase and also to prevent the oil used in the crankcase from migrating into the working space. Oil leakage into the working fluid can potentially foul heat exchangers and through decomposition add other gases to the working fluid, which would affect performance. However, experience in the NASA ASE project has shown that the first effect to be noticed is a fouling of the piston rings, which causes rough operation (vibrations) of the engine. The variable-stroke engine normally pressurizes the crankcase to the mean-pressure level of the working space and therefore requires an additional seal in the system. One seal must isolate the pressure swing in the working space from the mean pressure of the crankcase and also prevent oil migration into the working space. This seal has the high-level, time-varying working space pressure on one side and the mean pressure with oil lubrication on the other. The engine needs one seal of this type for each cylinder of the engine. The second seal is a rotary seal at the output shaft of the engine that must prevent the mean-pressure level of the crankcase from escaping to the outside atmosphere. This rotary seal has the oil-lubricated mean engine pressure on one side and the outside atmosphere on the other. Only one seal of this type is needed for each variable-stroke engine.

In the mean-pressure control engine a sliding seal must prevent the pressure level of the working space from escaping to the crankcase, which is at atmospheric pressure. This same seal must also prevent the oil from migrating into the working space. This seal operates with the high-level, time-varying working space pressure on one side and the outside atmosphere with lubrication oil on the other side. One seal of this type is needed for each cylinder of the engine.

Kinematic Stirling engines commonly utilize hydrogen or helium as the working fluid. Hydrogen-filled engines typically can be smaller than helium-filled engines for the same power level. However, some hydrogen will permeate through the high-temperature heater tubes (helium will not), resulting in a higher working fluid makeup requirement. Air or nitrogen can be used as the working fluid but result in substantially larger engines.

Mean-pressure-control kinematic engines typically have a crankshaft and flywheel system similar to that in a common internal combustion engine. During the expansion phase of the cycle, power is transmitted to the kinematic linkage from the thermodynamic cycle. Some of this power is stored in the inertia of the linkage and the flywheel. At another phase of the cycle some of this inertial energy stored in the kinematics is returned to the cycle as the work of compressing the working fluid. The efficiency of this storage system is very high and remains so over a wide range of speed.

FEATURES OF FREE-PISTON ENGINE

The FPSE is generally characterized by the lack of any linkage or kinematic system for either the transfer of power to the load or the timing of the piston motions. However some "free-piston" engines do provide displacer motion control with a linear electric motor or mechanical drive device. The engine is normally a resonant device with no oil system, piston stroke control system, or pressure control system. All FPSE's to date have been of the piston beta configuration with a power piston and a displacer. Such engines are currently being developed for use in space power applications, where long life and low specific mass are the major design drivers. Programs are under way to develop the FPSE for other terrestrial applications. These include generator sets, gas-fired heat pumps, and solar-dish electric power for utility service.

The FPSE is a resonant device that operates on the Stirling cycle. The power piston and the displacer resonate as the engine operates. The motions are governed by the masses of the piston and the displacer, along with the spring forces and damping that exist in the engine. Spring forces are supplied through the volume variation of the gas springs and the working space. The damping on the displacer is primarily due to the losses in the engine; the damping on the piston is primarily due to the load. The motions of the piston and the displacer follow the dynamic theory of spring mass systems with damping applied. Both the size of the spring and the damping coefficients are designed such that the motions cause the desired Stirling cycle to occur.

The FPSE power output is in the form of linear motion and therefore lends itself to three basic forms of power conversion: The power piston can drive a linear alternator that converts the engine power output to electricity; it can drive a linear pump that displaces a fluid; or it can drive a compressor that compresses a gas. Each of the loads has unique characteristics that can alter the engine operation. A linear alternator is very similar to a pure damper, but a compressor has some amount of spring content. A fluid pump is a form of Coulomb load, similar to pure friction. These spring and damping factors become part of the total spring, mass, and damping system that determines the motions of the piston and the displacer.

The mean pressure of an FPSE remains fixed during operation. The load conversion device is located in the pressure vessel of the engine. The engine can be designed so that there are no penetrations into the pressurized engine housing that require dynamic seals. The engine can therefore be hermetically sealed for long-life applications. With the mean pressure being maintained at some constant value, the power output is typically regulated through the load.

As the load against which the engine performs work is varied, the engine will respond by varying the stroke of the piston and the displacer, with the mean pressure and the frequency of the engine remaining fixed. The change in the load appears to the engine to be a change in the damping applied to the power piston. Through the dynamics that determine the spring mass system resonance, the change in piston damping alters the piston stroke, the displacer stroke, and the displacer motion relative to the power piston motion, yet has a negligible effect on the system resonant frequency. In a manner similar to the variable-stroke kinematic engine, the change in stroke of the FPSE alters the power output by changing the volume variation within the engine.

APPENDIX G

INDUSTRY RESPONSES

Cummins Power Generation, Inc.
Box 3005
Columbus, Indiana
47202-3005

March 13, 1990

Dr. J. Stuart Fordyce
Director of Aerospace Technology
National Aeronautics & Space
Administration
Lewis Research Center.
Cleveland, OH 44135

Dear Dr. Fordyce:

The following comments are a result of our meeting with Messrs. Beremand and Shaltens during their January 31 visit to review the recently completed Department of Energy (DOE) automotive Stirling engine program. As you know, Cummins Engine Company is currently pursuing the free-piston Stirling engine technology for solar electric conversion systems, so your review of the DOE funded kinematic Stirling engine is of interest.

The Stirling engine has a number of characteristics which make it an attractive alternative when compared to current diesel engines. Along with the known high efficiency are its capabilities for multi-fuel operation (which consists of a broad range of liquid and gaseous fuels) and its unique capability to use alternate heat sources such as solar energy. In addition, emissions from the Stirling engine are generally believed to meet today's standards for use in a light-duty truck application. The Stirling engine's total number of parts, as well as fewer moving parts, suggest that the potential exists for lower maintenance requirements and longer life/service intervals. Also, because the oil used for lubrication in the Stirling engine does not see the combustion products, oil and filter changes should be reduced significantly. Finally, the free-piston Stirling engine may have even longer life because it has even fewer moving parts than the kinematic type Stirling engine, and because oil is not required for lubrication, oil seals are not required.

Although the Stirling engine has a number of advantages, we believe the Stirling technology is in its infancy and requires substantial development prior to its introduction into a major marketplace such as for the automotive application even if the market becomes reality. Major unknowns are the manufacturing requirements and the total costs for an engine with radically different components, such as the high temperature heat exchangers and regenerators, when compared with technology used in current engines. The life capacity and mature cost of materials required in the high temperature environment of the Stirling also remain unknown. Other areas of risk include development of advanced high temperature lubricants (for dry bearings) and cost effective magnetic materials for linear alternators, currently proposed for the free-piston Stirling conversion systems. The complex heat transfer and fluid flow phenomenon inside the Stirling engine is still not well understood and requires additional work. In addition, larger capacity radiators for cooling the Stirling engine are required for all applications and the size may be impractical for today's automotive application.

With the existence of two fully developed commercial engines (diesel and spark ignition) in place, we believe that the high production volume required for the automotive market will be very difficult (if not impossible) to penetrate for any new engine. Introductory markets should focus on specialty applications which utilize the advantages of the Stirling engine, have initial low production requirements, have little or no competition and price sensitivity is not an issue. Engine size should be below 25 kW (33 hp) power levels until the manufacturing issues can be fully understood along with unit cost. At Cummins the successful demonstration of proof-of-design engines must be completed before entering into the manufacturing prototype stage. After demonstration of the technical goals, sufficient reliability and durability data along with in-service evaluations (or demonstration) must be obtained from prototype engines (at least 50 to 200 units) before a decision on engine production could be made. After starting the prototype phase, it would take from 5 to 7 years before mature market production could be achieved.

Introductory markets would include applications for power generation systems (such as solar electric Stirling systems) for remote areas, replacement power sources for areas such as California, specialty military niches, irrigation pumping systems, generator sets for pleasure boats, and other renewable energy conversion systems.

We believe that there should be an on-going cooperative effort between government and the U.S. industry in high risk development efforts such as the Stirling engine. Currently Cummins Engine Company is spending the majority of its development and research funds to meet the current (and future) EPA and California (CARB) regulated emission standards for our primary product, diesel engines. Few resources are left for the development and evaluation of future products, primarily because of the limited resources available for high risk technologies such as free-piston Stirling engines. Today there appears to be little government interest or financial support and no incentives exist for the private sector to engage in pursuing the high risk technologies which may be of benefit for the nation environmentally and to help create jobs in the U.S. job market.

In conclusion, it appears that a broad knowledge base has been provided under the DOE automotive Stirling engine program, however, the data provided shows that the kinematic engine has not met all of its technical goals. Based on this data, we do not believe that the next step is a government/industry cost-shared fleet demonstration program. However, we do believe that an on-going industry/government program is needed to reduce risk and to foster commericalization of high risk technologies such as the free-piston Stirling engine.

I hope this information is helpful to you for your report to the U.S. Congress.

If I can be of any further assistance, please get in touch.

Sincerely,

Jerome Davis

President

J.Davis/sb

Telephone: (812) 377-3743
Facsimile: (812) 377-3334

John P McTague
Vice President
Research

Ford Motor Company
P.O. Box 1603
Dearborn, Michigan 48121-1603

February 22, 1990

Dr. J. Stuart Fordyce
Director of Aerospace Technology
National Aeronautics and
  Space Administration
Lewis Research Center
Cleveland, OH 44135

Dear Dr. Fordyce:

In accordance with your request, representatives of my staff met with NASA and DOE representatives to receive an update on the status of Stirling engine technology. Unfortunately, due to a prior commitment, I was not able to attend the meeting, but I would like to provide you with our reactions to the presentation and our comments on the Stallings amendment.

As you are aware, Ford Motor Company discontinued development work on the Stirling engine in 1979. We took this step in order to concentrate our resources on technologies critical to the future of the company, including the development of those technologies required to meet fuel economy and emissions regulations. In the powertrain area, we felt that this objective could best be met, within the required time frame, by concentrating our efforts on improving the spark ignition (SI) piston engine.

In the future we are likely to face even more stringent regulatory requirements in the areas of fuel economy and emissions. Thus, the targets that the Stirling engine must meet in the future are even more demanding than those of the past.

Based on the vehicle data presented during the meeting and our own reviews of the Stirling program from time to time, we see some attractive attributes to the Stirling engine, namely its multifuel capability and its relatively noiseless operation. However, it appears to us that several significant open issues need to be resolved before Ford Motor Company would develop any renewed interest in this concept. These issues are as follows:

- There is no evidence that the fuel economy of the Stirling engine will equal or better the best-in-class 1990 SI piston engine technology, measured at equal vehicle performance. Actually, the fuel economy of the Stirling engine would have to be substantially better in order to warrant the investment in a totally new technology.

- There is no evidence that the 0.4 gram per mile NOx target can be met with the current Stirling technology. It should also be kept in mind that Tier II requirements in the current legislative proposals would require 0.2 gram per mile NOx by the year 2004. There certainly is no evidence that these goals are achievable with the current Stirling technology.

  The NOx control issue is of particular concern. In today's automotive emission control systems, NOx is catalytically reduced in the exhaust stream, and this technology makes it possible to reach the 0.4 grams per mile in many SI engine applications. In the case of the Stirling engine, however, the entire NOx control task must be performed within the burner since catalytic reduction is not possible in an exhaust stream containing excess oxygen. Achievement of the proposed 0.4 gram per mile or 0.2 grams per mile in the long term may well be beyond the capability of continuous combustion technology.

- We also question whether it will be possible to manufacture the Stirling engine in high production volumes at low cost with very high reliability. Our current assessment indicates that little work has been done in this area. Stirling engine manufacturing practices appear to be complex and costly, and certainly this concept would require large new investments in facilities and tooling that would have to be justified by major product benefits.

- We also have concerns about the packageability of Stirling engine systems, i.e. the engine plus cooling system, in the engine compartments of many of our future vehicles.

- Finally, there is the problem of working fluid containment which still appears to be unresolved.

According to our understanding, the Stallings amendment proposes that the next logical step is a government/industry cost-shared commercial demonstration program. Based on the significant open issues raised above, we do not agree with such an approach. Although we do not recommend additional government expenditures for the Stirling engine, if they are made available, they should be targeted at resolving these issues before commercialization is undertaken.

Sincerely,

John P. McTague

MAR 9* RECD

March 6, 1990

Mr. Donald G. Beremand
NASA Lewis Research Center
Stirling Technology Branch
21000 Brookpark Road, MS301-2
Cleveland, OH 44135

Subject: GRI's Stirling Engine Program

Dear Mr. Beremand:

This letter is in response to your request to obtain GRI's perspective on the prospects for commercialization of Stirling engines. I would like to share with you GRI's experiences and outlook regarding Stirling engines and to indicate what steps may be needed to improve the chances of commercializing the Stirling engine.

Since 1980 GRI has been supporting the development of stationary natural gas-fired Stirling engines as alternative prime movers to conventional internal combustion (IC) gas engines. The impetus for GRI's Stirling engine R&D program has been the Stirling's potential for lower emissions and less maintenance than conventional engines. To date, GRI has invested over $25 million in contractual R&D funds to develop a variety of stationary gas-fired kinematic, and free-piston Stirling engines for driving residential and small commercial vapor compression heat pumps and cogeneration systems. While these R&D efforts have advanced the state-of-the-art, attempts at commercializing the engines have been unsuccessful. Based on these experiences, we believe the Stirling engine cannot compete on a first cost basis with reciprocating IC engines, and that barring introduction of mass-produced markets for Stirling's, such as transportation, we believe it is unlikely that the Stirling engine cost can be sufficiently reduced to compete with conventional prime movers. However, we do believe the Stirling engine has unique attributes that no other prime mover can likely attain: very quiet operation, exceptionally low emissions and the potential for long periods between service. While many of the Stirling engine's attributes are intangible, they may in the long term provide the opportunity to achieve commercial success. For this reason, GRI has recently taken the position of maintaining a lower funding level technology base R&D program on Stirling engines to address key technical issues in order to improve their competitive position. As a consequence GRI's Stirling engine efforts are directed to two fronts, 1) an assessment of worldwide Stirling engine developments to determine the most commercially viable designs and level of their development, and 2) a technology base program directed toward finding solutions to technical problems that hinder the commercialization of Stirling engines. These R&D efforts are likely to be continued by GRI in the next few years.

Gas Research Institute, 8600 West Bryn Mawr Avenue, Chicago, Illinois 60631 312/399-8100

In regard to the commercialization of Stirling engine's for automotive applications it is GRI's belief that only government mandated legislation can create a market for low pollution gas engines such as the Stirling. At present, industry has not been willing to invest their resources in Stirling engines, that not only cost considerably more than state-of-the-art automotive engines, but whose attributes have not been sufficiently demonstrated to reduce the technical risks. For example, technical barriers such as weight penalty, slow start time and seal degradation, need to be overcome before any large investments can be justified. In addition, market barriers such as lack of customer incentives and lack of a service infrastructure have not been addressed.

To create the financial incentives for engine manufacturers to commercialize Stirling engines, it is an important first-step that the federal government pass pollution control legislation requiring further reductions in automotive fleet average emissions. Without such legislation, it is unlikely that the Stirling engine can compete in the marketplace.

I have filled out the attached questionnaire you requested that suggests the type/size of the proposed Stirling engine automotive fleet demonstration program. Assuming "success" of the demonstration, I have listed the timetables and possible financial investments needed to bring the automotive Stirling engine into mature production.

If you require any further information on GRI's Stirling engine program, please feel free to contact me.

Sincerely,

Michael Clinch

J. M. Clinch, Ph.D.
Senior Project Manager
Commercial Space Conditioning

JMC/jad

QUESTIONS FOR INDUSTRY

1. What **advantages** do you see for Stirling engine that make it attractive to you as a manufacturer? Potential for lower pollutant emissions and longer maintenance intervals at a modest cost premium over conventional engines.

2. What are the **disadvantages** or **shortcomings** of Stirling that might discourage you to manufacture Stirling engine? Uncertainty of market for Stirlings. Insufficient data on life, reliability & failure modes of engines.

3. What **technology barriers** do you believe exist for the Stirling? Slow start time. High temperature heater head problems. Seal problems.

4. What are the **market needs** for a new type of engine such as Stirling? Legislation which creates market for low pollution engine.

5. What **market barriers** exist for a new type of engine such as Stirling? Engine cost & weight are major barriers. Also lack of service infrastructure.

6. What do you see as the **initial** application(s) and market(s) for the Stirling engine?

Application(s) and Engine size(s)?
Government fleet vehicles eg. Post Office ASE size (40-80hp)
Initial market sizes and initial engine cost?
10,000/year $5,000/engine (ASE size)
Initial production run and mature engine cost?
2,000 at $3,000/engine
How many years before mature market production? Annual production? 10 years after initial market. Annual production depends on pollution control legislation. Legislation will create market and size of market.

7. Describe a demonstration program that you would require before entering into initial production of a new type of engine such as Stirling?

Number of engines? 250

Type of testing? City, Suburban, Fleets, North-South Climates (50 of each)

Component and system performance
Endurance or life and reliability
In-service evaluations
] All

8. What is your estimate (timetable) to bring a new engine such as Stirling into production?

8 years for the design and development?
6 years to demonstrate performance? endurance? ASE size?
2 years for in-service evaluations? ASE size?
12 years to initial production? 10,000 size? plant cost? $100 million
16 years to mature production? 500,000 size? plant cost? $400 million

9. What is governments role in the commercialization of a new engine such as Stirling? Why? Pass legislation requiring a moving reduction in Fleet average emissions. Support demonstration program with Federal, State & local government agencies.

10. Considering the advantages attributed to Stirling and the progress made in advancing Stirling technology, why has industry not been interested in pursuing it? No incentives to pursue Stirling technology. Stirling engines cost more & are heavier than conventional engines so why develop engine like Stirling unless you have to.

GM

General Motors Research Laboratories
Warren, Michigan 48090-9055

February 6, 1990

Mr. Richard K. Shaltens MS 301-2
NASA Lewis Research Center
21000 Brook Park Road
Cleveland, OH 44135

Dear Dick:

We appreciated the opportunity to comment on the automotive Stirling engine during your visit of January 23, 1990. Our opinions are based on our own experience with the Stirling engine when it was an active project here during the decade of the 1960s, and also on our tests of the Mod I engine installed in the Spirit automobile in 1984, conducted in a cooperative DOE program. These comments are made from the position of a company in the business of producing automobiles and light- and medium-duty trucks.

The automotive Stirling engine can claim some advantages relative to the generic internal combustion engine. It is reasonably quiet, can burn alternative fuels, and has a well shaped torque curve. However, we have also made the automotive gasoline engine reasonably quiet, and it, too, will operate on the leading alternative fuels proposed for highway vehicles, viz., M85, methanol and natural gas. Although there is always room for improvement in the torque-curve shape of the conventional engine, the transmission satisfactorily compensates for its deficiencies.

These attributes of the Stirling engine must be weighed against its shortcomings, as follows:

1. In our view, it is too large, heavy and expensive to be competitive with the spark-ignition engine that dominates the automotive field.
2. In our evaluation, it showed unacceptably poor fuel economy without commensurate compensation in performance capability.
3. Regulators are considering a future NOx standard of 0.2 g/mi. We are not convinced the Stirling engine can satisfy such a difficult standard, since it can derive no help from a reducing catalyst.

Let's Get It Together
SAFETY BELTS SAVE LIVES

4. We think the consumer would object to the time spent waiting for a cold engine to achieve operating temperature. This problem seems inherent to external combustion engines, a point made obvious to us in our steam engine experience of the late 1960s.

5. We are convinced the consumer would not accept the current hydrogen leakage rate. Time and/or miles between service stops for replenishment of hydrogen needs to be prolonged to match infrequent service stops already accepted with current cars, e.g., changing oil.

6. Although the Stirling Spirit performed well in the wind-tunnel cooling tests we ran in 1984, we are still concerned about the unusual situations, e.g., grade climbing in a desert climate, where the cooling fans would cycle on to control coolant temperature. The reason for this concern is the sizable fraction of available engine power consumed by the normally inoperative cooling fans, which would be reflected as a sudden substantial drop in performance capability.

Because of these points, we foresee no place for the Stirling engine in our present business. This being the situation, we see no point in commenting on a demonstration program. There may, of course, be non-automotive applications where the Stirling engine proves attractive.

We cannot speak with any authority on potential applications outside of our segment of the automotive field. However, possibilities that come to mind include (1) the derivation of power from solar energy, (2) use in remote geographical areas where conventional liquid fuels might have to replaced by solid fuels like wood, peat, or coal, (3) applications where an engine could advantageously be operated on stored heat, and (4) marine (underwater?) use, where the availability of a large cold heat sink might benefit the Stirling cycle. It seems likely that in any of these applications, the ability of the engine to contain its charge of working fluid for prolonged periods would be essential.

Although in our experience, the Stirling engine has proven to be a poor match to the requirements of the light-duty highway vehicle, this in no way reflects on the competence of your prime contractor, MTI. During our interactions with them, we were impressed with their approach to the project and with the capabilities and diligence of their people. Congress needs to appreciate that when the government elects to pursue high-risk alternative powerplants for the automotive sector, this inherently entails a high risk of failing to meet program objectives. That is the nature of research and is not, in the present case, the fault of MTI.

Page 3
February 6, 1990

We understand that development of the Stirling engine is expected to continue for non-automotive applications. We plan to watch those developments, just as we follow progress on a variety of other powertrain options, in case the evolution of our business alters the engine situation. Meanwhile, if the Mod II engine were available for test in a vehicle, we would seriously consider evaluating it at no charge, just as we did the Mod I in 1984, in order to make certain that we have not missed anything. We would be most interested in a passenger-car installation, with automatic transmission, since that is the heart of our business. In decreasing order of interest are a passenger car with a manual transmission and a truck or van with any type of transmission.

Sincerely,

Chuck

Charles A. Amann
Research Fellow
Executive Department

CAA:mjb

JOHN DEERE TECHNOLOGIES INTERNATIONAL, INC.

JOHN DEERE ROAD MOLINE ILLINOIS 61265 8098 U S A

EDWARD S. WRIGHT
President

12 February 1990

Dr. J. Stuart Fordyce
Director of Aerospace Technology
National Aeronautics & Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Dear Dr. Fordyce:

It was a pleasure to renew old acquaintances with Messrs. Beremand and Shaltens on their visit January 30th. At their request, I am responding to your letter of 26 December 1989.

As you know, Deere & Company is one of the world's foremost engine design development and manufacturing organizations. We are well known for the millions of reliable cost-effective engines we have manufactured since 1917 for farm tractors and a variety of other farm and construction equipment, including the production of close to three million diesel engines. In fact, we are the nation's leading producer of off-highway diesels under 300 hp. These engines have consistently led their competition in such innovations as rotary fuel pumps, turbocharging, intercooling and high output.

Perhaps less well known is Deere's innovation in activities involving alternative engines, such as gas turbine engines, rotary engines, and Stirling engines. In the years 1965 through 1972, for example, Deere designed and tested extensively an innovative gas turbine engine for tractor and earthmoving applications which represented a substantial breakthrough in both manufacturing cost and performance. This engine was developed to production status but was not committed to production because it is *extremely* difficult and risky to introduce a completely new type of engine to the commercial marketplace by *any* single company. An extensive evaluation resulted in an executive decision to commit to a diesel engine, which was under simultaneous development for the intended application. This decision was a business decision heavily influenced by the risk of introducing a new type of engine.

Currently, Deere & Company is committed to produce an innovative stratified charge rotary engine. We are the *only* engine company in the world currently committed to produce this engine. The decision to commit to this risky path was possible *only* because of substantial R&D funding by, and production requirements of, the U.S. military.

FEB 20 1990

Dr. J. Stuart Fordyce
12 February 1990
Page Two

It is apparent that Deere is exactly the type of innovator required to commercialize a totally new engine like the Stirling engine. With this prospect in mind, Deere invested considerable resources from 1985 through 1989 in thoroughly investigating Stirling Engine technology and the manufacturing costs and techniques necessary to make it practical.

The results of this investigation were presented in testimony to Congress in 1988 and 1989 when we explained in detail what was needed to commercialize the engine. Namely to conduct a commercial based field test in the hands of potential buyers of a statistically significant number of prototype engines. We estimated a cost of $85 million for this project of which $20 million (25%) was necessary to be provided by the government.

Unfortunately, that support was not forthcoming. We dropped our project, the skilled, experienced team we assembled was disbanded, and the net result is that neither we, the engine developer, the Department of Energy, the Congress, the potential customers, or the engineering community have the foggiest idea whether the engine should have been commercialized or not.

What is known is that the taxpayer has paid $130 million for a currently useless technology--useless not because of any inherent defect, but because the Department of Energy naively believed that the technology had been developed to the point where an engine manufacturer could make rational decisions to commit large scale resources to its commercial deployment.

Since we have already stated our position fully to the Department of Energy, NASA, and the Congress, detailed answers to the attached questionnaire seem superfluous. Nevertheless, we are glad to reply briefly in the spirit of cooperation we have always maintained towards this project.

Sincerely,

Edward S Wright

Edward S. Wright
President
John Deere Technologies International, Inc.
Phone 309/765-5462

mgm
enclosure

1. What advantages do you see for Stirling engine that make it attractive to you as a manufacturer?
   It is efficient, cost effective, and capable of operation from any reasonable heat source, including alternative fuels, solar collectors, and waste heat.

2. What are the disadvantages or shortcomings of Stirling that might discourage you to manufacture Stirling engine?
   The major known disadvantage is that it is still a laboratory engine and the risks inherent in commercializing it are too high for a profit making company.

3. What technology **barriers** do you believe exist for the Stirling?
   We do not see any technology barriers. Obviously, a great deal of optimizing, value engineering, and reliability growth needs to be accomplished.

4. What are the market **needs** for a new type of engine such as Stirling?
   An initial introductory market which is willing to pay a modest premium for the engine advantages is a necessity. For example, we identified a need in urban light delivery fleets for the ASE.

5. What market **barriers** exist for a new type of engine such as Stirling?
   The market barriers are substantial. Among others, risk of committing to new technology, high initial selling price, revenue lag between initial order and reorder, fact that *no* sales can be realized until product is tested extensively in customer's hands, etc..

6. What do you see as the initial application(s) and market(s) for the Stirling engine?
   I have no idea. There was a potential in the alternative fuel urban light delivery fleet market, but that opportunity is past.

7. Describe a demonstration program that you would require before entering into initial production of a new type of engine such as Stirling?
   As we extensively explained at the time we were willing to tests its viability, at least forty engines in testing for at least eighteen months in customer's hands would be a minimum possible requirement.

8. What is your estimate (timetable) to bring a new engine such as Stirling into production?

Specifically with regard to the ASE:

10 years for the design and development?

3* years to demonstrate performance? endurance? ________ size?

3* years for in-service evaluations? ________ size?

3* years to initial production? ________ size? plant cost?

6 years to mature production? ________ size? plant cost?

19 Years Total ***to be conducted concurrently**

9. What is government's role in the commercialization of a new engine such as Stirling? Why?

Based on our experience, where the government refused to fund the logical last stage of Stirling engine development while continuing to fund impractical, unproven gas turbine developments, the government's role in this type of commercialization needs to be strongly reassessed.

10. Considering the advantages attributed to Stirling and the progress made in advancing Stirling technology, why has industry not been interested in pursing it?

On the contrary, industry has been interested in pursuing the Stirling Engine. It was the government's failure to continue to risk-share in a highly risky venture which sunk the ASE program.

Kennedy Engine Company, Inc.
PHONE (601) 392-2200 FAX 601-392-9507
MOTSIE ROAD AT I-10 (CEDAR LAKE EXIT)-RT. 6
BILOXI, MISSISSIPPI 39532

1. Advantages of the Stirling engine that make it attractive to Kennedy Engine Company as a manufacturer would include the growing need to solve air pollution problems and to reduce the nation's reliance on fossil fuels. The future demands will only increase as the nation struggles to meet clean air and water standards thus insuring a future market for the production of the Stirling engine.

2. Disadvantages or obstacles to overcome in initiating the manufacture of the Stirling engine would all bear on the fact that there is no manufacturing infrastructure in place for this new technology. Because establishment of that infrastructure would require a large capital investment and because the venture would be viewed as high risk by possible investors, loan and seed funding will be difficult to obtain. There is at present only a limited ready market for the Stirling engine.

3. It is not possible for Kennedy Engine Company to predict what technology barriers exist for the Stirling engine because Kennedy Engine Company has not had an opportunity to evaluate the engine by way of hands-on testing. Future government programing of Stirling engine commercialization should include making the engine available for testing by prospective manufacturers.

4. Infrastructure and training would be needed to market a new engine such as the Stirling. Existing engine business infrastructure could be adapted to the special requirements of the Stirling technology.

5. The lack of an established network for service, training, and spare parts would present initial market barriers for the Stirling engine. Also, the established engine manufacturers are not likely to welcome the entrance of a new engine competitor in the marketplace.

6. Kennedy Engine Company currently has standing orders for Stirling engines. The engine application would be in stationary generator sets in the 50KW to 200KW range. The initial market size would be between 2,500 and 3,000 generator sets at a cost of $50,000.00 to $60,000.00 per unit.

7. Kennedy Engine Company would require a demonstration program that would allow it to evaluate concepts/prototypes with hands-on demonstrations with Stirling engines in several modes of operation and in multi-fuel conditions. We would like to demonstrate life of engine and reliability factors. Prospective customers would require field test engines for their own

evaluation. In order to promote the commercialization of the Stirling technology, we believe that the government should conduct a similar program.

8. We estimate the following timetable to bring a new engine such as the Stirling into production:

5 years for design and development
3-5 years to demonstrate performance
1-2 years to demonstrate endurance
10 years for in-service evaluations
3-5 years to initial production
Plant cost- $50,000,000.00
8 years to mature production

9. We believe that the government has the responsibility to help achieve the goal of clean air in this country and to assume some of the risk and cost in establishing a new manufacturing infrastructure to further this objective. The market can then dictate the need.

10. Industry has had little incentive to pursue the Stirling engine technology since the clean air standards have been formulating slowly and enforcement still remains questionable. The establishment of infrastructure is so capital intensive and risky so as to deter most businesses from venturing into it.

APPENDIX H

AGENCY RESPONSES

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AIR FORCE SYSTEMS COMMAND
ANDREWS AIR FORCE BASE DC 20334-5000

JAN 8 1990

REPLY TO ATTN OF: LGT

SUBJECT: Stirling Engine Technology for Use by the Automotive Industry

TO: Mr Richard K. Shaltens
NASA Lewis Research Center
Stirling Engine Project Office/
MS301-2
2100 Brook Park Road
Cleveland OH 44135

1. The Air Force Management and Equipment Evaluation Program (MEEP) was invited by the National Aeronautics and Space Administration (NASA) to participate in the testing and evaluation of the Stirling technology in November 1985. Purpose of the testing/evaluation was to assess the feasibility of using the Stirling technology for use in the automotive industry.

2. Testing evaluation of the Mod I version of the Stirling engine was conducted while installed in a multipurpose van and a D150 pick-up truck by our four field MEEP activities. Summary of the results and our position on the commercialization of the Stirling technology is as follows:

a. The potential of reducing maintenance cost benefits versus the conventional gasoline engine:

(1) One ignition plug in lieu of four, six, or eight spark plugs.

(2) No ignition points, stator, rotor, distributor cap or ignition wiring.

(3) No catalytic converter.

(4) No muffler.

(5) No oil or filter changes.

(6) No engine tune ups.

(7) Fewer moving parts to wear or cause friction.

(8) Higher operating efficiency.

b. Other benefits

(1) Lower noise level

JAN 12 1990

(2) Somewhat increased fuel economy during open highway operation.

(3) Reduced emissions.

(4) Operates on multifuel, i.e., leaded/unleaded gas, diesel, and JP-4 aircraft fuel.

c. Shortfalls/disadvantages versus the conventional gasoline engine.

(1) Experienced difficulty during cold weather use in getting the Stirling engine to start. This was usually associated with the fuel control system.

(2) Excessive hydrogen (H2) leakage during first part of the evaluation. However, the problem improved as the contractor technicians gained more experience.

(3) Numerous failures in the electronic external control systems.

During the evaluation period, it was necessary to have contractor technicians go to the test/evaluation site to troubleshoot, repair or replace failed component parts/systems. This was necessitated by the new technology. There is no infrastructure developed that would allow you to go to a local repair shop or manufacturer/dealer to get malfunctions corrected. In addition, our repair/service technicians are not yet trained in the Stirling technology or mechanical components.

d. Recommended demonstration fleet.

(1) We do not recommend further demonstration/evaluation unless there are stated interests from a manufacturer to develop a prototype fleet equipped with the Stirling technology automotive engine.

(2) If this develops, the Air Force MEEP would be willing to evaluate a demonstration fleet of up to 50 vehicles.

e. Stirling demonstration results.

(1) The evaluation/demonstration results of the Stirling technology were positive. It was demonstrated through our field evaluation that the Stirling technology can be adopted for use by the automotive industry. However, we are not in the position to evaluate or assess whether this would or could be cost effective.

f. Long term sponsor contributions.

(1) Charter of the Air Force MEEP is to test and evaluate products that have already been developed and are on the market, at no cost to the Air Force. We cannot provide or commit funding of the Stirling technology. We operate under the 'Try Before You Buy' concept prior to recommending adoption for Air Force use.

(2) The MEEP will participate in further testing/evaluation of the Stirling technology if and when asked/invited to do so. However, we do recommend that there be some involvement by an interested manufacturer prior to further testing/evaluation of this technology.

3. We hope that this information will be sufficient for your use in putting together a draft report on the commercialization assessment of the Stirling technology. In addition, we appreciate the opportunity of working with all of the agencies involved in this endeavor. If we can be of further assistance, my point of contact is Mr Ezra Lane, (301) 981-3206.

Fred R. Hester

FRED R. HESTER
Director of Transportation
Deputy for Logistics

cc: HQ USAF/LETN
NASA Wash DC (Mr Ault)

FEB 1 1990

Department of Energy
Washington, DC 20585

January 17, 1990

Mr. Leonard A. Ault
Acting Director
Technology Utilization Division
NASA Headquarters (CU)
Washington, DC 20546

Dear Mr. Ault:

During our recent meeting at NASA Headquarters, in connection with the Stirling commercialization bill HR 1759, we discussed the DOE experience with the demonstration of electric and hybrid vehicles. I have written below some background information about the demonstration and some comments on lessons learned.

On September 17, 1976, the U.S. Congress passed the Electric and Hybrid Vehicle Research, Development and Demonstration Act (Public Law 94-413). The Act established a multi-year project to demonstrate the economic and technological practicability of using electric and hybrid vehicles on the Nation's roads. The Act was conceived at the height of the Nation's first major energy crisis. The Act, as amended, provided for research and development projects, promulgation of vehicle performance and safety standards, a program of loan guarantees and small business planning grants, special studies, and other related activities. It also provided for vehicle demonstrations involving Federal, state and local governments, private citizens, and commercial/industrial organizations. Specific goals of the demonstration project were to:

-Demonstrate the economic and technological practicability of electric and hybrid vehicles for personal and commercial use,

-Promote the substitution of electric and hybrid vehicles for many gasoline and diesel-powered vehicles currently used in routine short-haul, low-load applications, and

-Facilitate the use of electric and hybrid vehicles in lieu of gasoline and diesel powered motor vehicles and develop recommendations for overcoming barriers to their use.

The authorized program was never fully funded by the Appropriations Committee. Activities were conducted in the period of 1976 to 1982. These activities were as follows:

-Opportunity and Risk Assessments (OPRA) - initially it is useful to conduct an assessment of opportunistic and risks which could be significant in achieving the program goals. The primary areas of concern are vehicle technology development, industry commercialization as influenced by incentives, user acceptance and market development, institutional barriers, organizational and policy decisions internal to the Federal Government and long term energy and environmental impacts,

-Marketing and Service demonstrations - conceived in order to test markets and to begin the development of an electric vehicle distribution and servicing infrastructure,

-Site Operators - programmatic operators were established throughout the USA to demonstrate the utility of electric vehicles,

-Test and Evaluation - site operators determined the technical and economic problems of operating fleets of electric vehicles, and

-Dealership Program - an attempt was made to establish electric and hybrid vehicle dealerships throughout the USA.

Aside from the benefits that might yet be achieved, the marketing and service demonstration programs did not achieve their objectives. The concept was a valid expression of Congressional objectives. However, because of an immature technology, an inadequate industrial commitment, a general slowdown in the Nation's economy, and unforeseen changes in energy economics and accompanying shifts in government policy, the program was terminated. While a modest level of activity in demonstrations could have been justified because of the feeling of urgency which pervaded the energy program environment in the mid 1970s, retrospective analysis shows that the dealership program was premature considering the circumstances which were emerging in the early 1980s.

Experience has determined that certain basic requirements should be applied to vehicle demonstrations. Companies producing the demonstration vehicles must have sufficient capital to cover start-up costs and maintain support through the initial deployment of the vehicle fleet. Demonstration fleets should be of sufficient size to allow for dedicated service personnel. It is important to the success of the demonstration that service personnel be given adequate technical training by vehicle manufacturers. Documentation and service procedures from the manufacturers must be complete and accurate. There must be provisions for spare parts in an efficient manner. Demonstration sites must be selected with compatible end-users in a variety of climates.

It is important to distinguish that the electric vehicle demonstration was a market demonstration. That is its goal was to effectively bootstrap an entire industry into existence. In order to achieve that goal, it included all phases of a prototype industry, including manufacturing, marketing, sale, and service. The goal also dictated a fairly large demonstration and well over a 1000 vehicles were involved. By contrast, for the Stirling engine, a more modest technology demonstration may be more appropriate. A technology demonstration involves about 50 to 100 vehicles. These vehicles are usually identical and concentrated in a small number of fleets, so that maintenance activities can be conducted by properly trained full time personnel. The vehicles can be assigned to different users to evaluate user reactions.

The technology demonstration concentrates on an evaluation of vehicle and subsystem performance, reliability, and cost in a semicontrolled environment. It does not attempt to create a prototype industry or to simulate actual free market conditions. The vehicles are assigned to trained personnel and subjected to periodic service and maintenance procedures to assure reliable operation.

The electric vehicle demonstration programs did provide an opportunity for "hands on" learning by electric vehicle manufacturers and users alike. The Site Operator program is still in existence, but on a smaller scale. This program has provided a steady stream of feedback from the end-users to the technology developers. This feedback resulted in identification and resolution of many technical deficiencies. The vehicles that are being produce today have benefited from this experience.

It should also be noted that we have available for your consideration documentation on many phases of the electric vehicle demonstration project. Some of the evaluation documents are attached. In addition, a complete project plan, requirements and guidelines for site operators, and sample operators' conference proceedings are available.

The above discussion should be helpful in defining our experience in the commercialization of vehicle systems. I hope this information and background are helpful to your efforts in Stirling commercialization. Please do not hesitate to contact me for any further information.

Sincerely,

Richard J Miner for

Kenneth L. Heitner
Acting Manager, Test & Evaluation
Electric and Hybrid Propulsion Division

Enclosures

cc: Richard K. Shaltens
Stirling Technology Branch (MS 301-2)
Lewis Research Center
2100 Brookpark Road
Cleveland, Ohio 44135

Department of Energy
Washington, DC 20585

Mr. Richard K. Shaltens
NASA Lewis Research Center
MS 301-2 Stirling Technology Branch
21000 Brookpark Road
Cleveland, OH 44135

Dear Dick:

This is in response to your request for Department of Energy (DOE) input to your Inter-agency Stirling Commercialization Study. The response focuses on specific areas that you have designated for DOE participation.

ASE Program Assessment:

The accomplishments of the Automotive Stirling Engine (ASE) program have been significant. The Stirling engine technology at the beginning of the ASE program was at the stage of a laboratory curiosity. Today at the end of the ASE program the Stirling engine is operating reliably in real vehicles. Vehicle exhaust gas emissions, driveability, vehicle installation, engine manufacturability and projected cost have been established. This is a major accomplishment and NASA and the ASE contractors are credited with a job well done. As a result of the ASE program, a large technology base including designs for both Mod I and Mod II engines, engine component test data, engineering analyses, and detailed design requirements are available for industry's use in any further commercialization activities. It is the position of DOE that commercialization efforts focused on demonstrations with potential customers or for further product development should be supported solely by industry.

Potential Energy Benefits:

The data from engine dynamometer testing by Mechanical Technology, Inc. (MTI) support a 25%-30% improvement in vehicle fuel economy which would meet the original program goal. However, this has not been demonstrated in a Mod II powered vehicle system. The possibility exists that the Mod II engine could be malfunctioning but, there are no resources to perform the appropriate engine check out to verify that the engine is functioning properly.

United States Post Office (USPO) test results comparing the Environmental Protection Agency (EPA) combined cycle fuel economy for the Stirling versus the spark ignition showed a 4% to 6% improvement for the Stirling while it took 42% longer to accelerate to 55 MPH with the Stirling engine. The potential of the Stirling powered automobile to save a significant amount of energy or petroleum has not yet been demonstrated.

MAR 23 REC'D

Alternative Fuels Projections:

The use of alternative fuels in place of petroleum derived fuels is a viable means of significantly reducing U.S. dependency on petroleum. The leading near term candidates, alcohols and natural gas are to a very limited extent already displacing petroleum derived fuels. For the longer term, it would be desirable to derive transportation fuels from abundant domestic resources such as coal and oil-shale, although those synthesis processes may have negative greenhouse gas impacts. These resources can be processed into a variety of hydrocarbon fuels similar to gasoline and diesel fuel and into oxygenates such as methanol. However, present high production costs hinder their widespread acceptance. There is much renewed interest currently on alternative fuels for potential air quality benefits. DOE efforts in this area are attempting to insure that inadequate utilization technology is not a barrier to the widespread use of fuels which can be derived from our long term resources.

The Department has been conducting research programs for over a dozen years to develop fuels which are acceptable to the marketplace with regards to availability, cost, and environmental impacts. Many problems concerning utilization of methanol have been resolved to the extent that first-generation flexible-fuel light-duty vehicles are in production. For heavy duty engines, the technology is considerably less developed although new diesel engines emissions requirements have made methanol an attractive alternative fuel candidate. Heavy-duty natural gas engines are also the subject of renewed interest for reducing air pollution. Natural gas, which is primarily methane, appears to offer excellent qualities, including abundant sources and possible reductions in exhaust emissions. One disadvantage, however,is lower energy content and hence reduced driving range compared to other fuel options. The near future of natural gas, (as compressed natural gas), appears most promising to fleet operations and buses where these restrictions are of less concern.

It is generally accepted that the external combustion in the Stirling will allow more flexibility to accommodate alternative fuels. However, it appears that the fuels that are likely to become dominant are compatible with existing engines as a prerequisite. These alternative fuels do not appear to generate a demand for the Stirling engine.

Future Energy Assessment:

The Department predicts net petroleum imports of crude oil and refined products will increase from 6.3 million barrels per day in 1988 to 10.2 million barrels per day in 2000. The forecast for 2000 reflects the net imports divided by total petroleum demand of 55 percent up from 37 percent in 1988. Most of the projected future increase for petroleum demand is for industrial and farm diesel and jet fuel, but not for gasoline (thanks to increasing auto fuel efficiency). Gasoline price is predicted to increase very little between now and the year 2000.

Improved fuel economy will continue to be a priority from a national point of view, especially with the desire to lower CO2 production. Fuel cost, however, is becoming a smaller fraction of overall cost of the automobile and the consumer is growing less interested in the importance of fuel economy. The effect of these factors is that the Federal Government will have to exert an increasing influence to cause more fuel efficient engines to be developed.

Future Engine Projections:

A recent assessment of near-term technological improvements to automobiles to improve fuel economy has been performed under sponsorship of the Department of Energy, Office of Policy Integration. While endorsed by neither the Government nor industry at this time, it does represent an up-to-date evaluation of the potential for near term technical improvement in the auto industry. The following information is drawn from the assessment.

Two of the most important changes in engine technology are the shift to overhead camshaft (OHC) engines and the incorporation of 4-valve technology. Both Ford and GM are planning the introduction of a variety of OHC engines in the 1991-1994 time frame while Chrysler was already utilizing OHC engines in the majority of its 1987 fleet. All manufacturers will also introduce 4-valve/cylinder technology in a variety of 4, 6, and 8-cylinder engine models but it is anticipated that both the 4-valve and 2-valve versions will be sold with the former as an option. A near 100 percent transition to OHC is expected to occur by 2000 in cars. In Light Duty Trucks (LDT's) it is estimated that the introduction of OHC engines will lag their introduction in cars by 4 to 5 years, and overhead valve engines will continue to predominant in the full-size models even in 2000. The use of 4-valve technology will be limited to compact LDT's. However, it is anticipated that 3-valve single overhead cam engines are likely to be used in the standard size pickup trucks by 2001.

Engine friction reduction will occur by the use of roller cam followers (these were adopted in many engines in 1988/1989, while several engine models incorporated them as early as 1985) and the use of low mass pistons and rods coupled with low tension piston rings. The latter technology was used in some engines in 1986 and 1987, but further evolutionary improvements in friction reduction are expected by 1995 and again by 2001. The use of on-center bores in the 90 degree v-6 engine from GM also provides some additional improvement in fuel economy in 1988/1989. These technologies will also see universal use in the LDT fleet by 2001.

Increased use of fuel injection has already occurred in 1988/1989, but gradual transition from throttle body fuel injection to multiport fuel injection will occur in the 1990-1995 time frame. (This will, in part, be driven by the emission standards and other emission related regulations). In the post-1995 time frame, variable valve timing is expected to be used on many (if not all) 4-valve engines employing double overhead camshafts (DOHC). Turbocharging and supercharging will be offered in a few sporty model cars but their widespread use is not foreseen. The following fuel economy gains for these technologies are predicted to be realized by the year 2000: overhead camshaft - 6%, roller cam followers - 1.5%, low friction pistons/rings - 2%, multiport fuel injection over throttle body fuel injection - 10%.

As the fuel economy of the spark ignition continues to improve and as fuel cost becomes a smaller part of automobile total life cycle cost, it is becoming more difficult to justify the industry investment required to tool up, produce and support a new engine like the Stirling.

Past Fleet Demonstrations:

This subject is addressed in a letter to Lennard Ault dated January 17, 1990, in which Kenneth Heitner of this office discusses the DOE experience with Electric vehicle demonstrations.

The opportunity to participate with NASA and the other agencies on this study is very much appreciated. If there is anything in addition, that we can do to assist you in the preparation of your report to Congress, please don't hesitate to call me.

Sincerely,

Melvin H. Chiogioji, Director
Office of Transportation System
Conservation and Renewable Energy

cc: Lennard Ault, NASA TU

U.S. Department of Transportation
Urban Mass Transportation Administration

Headquarters

400 7th Street S.W.
Washington, D.C. 20590

JAN 31 1990

Mr. Leonard A. Ault
Acting Director
Technology Utilization Division
National Aeronautics and
  Space Administration
Washington, DC 20590

Dear Mr. Ault:

I enjoyed participating in the meetings on the commercialization study of the Stirling Engine. I believe that the Stirling Engine is a potential engine alternative to compressed natural gas, methanol, and other alternative fueled engines being considered by the transit industry to meet the Environmental Protection Agency's (EPA) 1991 particulate emissions requirement for transit buses. The multi-fuel capability of the Stirling Engine makes the transit agencies less dependent on diesel fuel sources.

These benefits can only be obtained if the Stirling Engine can be developed for transit buses, meet the 1991 EPA particulate emissions requirements of 0.10 grams per brake-horsepower for transit buses, and be cost competitive with other engine technologies.

Although the technical feasibility of the Stirling Engine technology has been demonstrated, we believe it is not ready for transit use. Extensive development and testing work are required before transit agencies would accept or consider to purchase buses outfitted with Stirling Engines. The most appropriate applications would be small carefully controlled demonstrations where proper technical support and evaluation personnel can be provided by the developer. If you have any questions regarding our position of the Stirling Engine please contact me at 202-366-0220.

Sincerely,

George I. Izumi
Program Manager

JAN 22 1990

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ANN ARBOR, MICHIGAN 48105

JAN 16 1990

OFFICE OF
AIR AND RADIATION

Mr. Richard Shaltens
MS 301-2
NASA Lewis
21000 Brookpark Road
Cleveland, OH 44135

Dear Mr. Shaltens:

Based on our recent telephone conversation, I understand that you are interested in what emission requirements vehicles powered by Stirling engines will have to meet.

The emission standards that future vehicles will be required to meet are the subject of Congressional debate as I write this letter. Therefore, the best guidance that I can give you is a range. The range of Federal requirements is taken from the enclosed paper that summarizes current proposals in its Table 1. The California requirements are those currently under consideration for the future.

In your study of the Stirling engine, don't fall into the trap of considering only exhaust emissions. As the enclosed paper clearly indicates, emissions other than exhaust emissions may be the more important part of the future emissions picture as far as the volatile organic emissions go. The emissions of these hydrocarbons are a strong function of the fuel used and the control system used. Most of the work done to date with alternative engines (including the Stirling) has ignored this, so the prototype vehicles that currently exist would all probably fail badly in meeting stringent evaporative, refueling, and running loss standards.

Also don't forget particulate emissions. If you use a distillate-type fuel, like those with which much Stirling engine development has been conducted, you will need to look at particulate emissions too.

Another aspect for the future is alternative-fuel capability. The candidates are: natural gas, ethanol, methanol, LPG, and reformulated gasoline. Engines that can use all of the fuels clearly and efficiently may rank higher.

If you try to compute emission results using burner rig data, emission index (g/kg fuel) results, and fuel consumption, please caveat the results extensively. Thermal and speed/load transients are very important for low emissions and not much burner data exists for those operating modes. When using the burner rig data fabrication approach, don't forget the Stirling engine warm-up time. As clearly pointed out by Amann in SAE Paper 891666, the burner operates, consumes fuel, and pollutes while the heater head is coming up to temperature, and fuel and emissions also have to be accounted for.

The range of future Federal standards can be obtained from the enclosure. California is considering non-methane hydrocarbon requirements of 0.125 grams per mile, 0.075 grams per mile, and 0.040 grams per mile. California basically has a 0.015 grams per mile formaldehyde standard also.

With respect to particulates, I'm estimating that something in the range of 0.20 grams per mile (the current Federal range) to 0.08 grams per mile, California's requirement, will be the numbers to consider.

Good luck on your study. If you can drop by our lab when you visit Ford and GM, please let us know.

Sincerely yours,

Karl H. Hellman

Karl H. Hellman, Chief
Control Technology and Applications Branch

Enclosure

cc: G. Piotrowski, CTAB (w/o enc)

198

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ANN ARBOR, MICHIGAN 48105

OFFICE OF
AIR AND RADIATION

29

Mr. Richard Shaltens
MS 301-2
NASA Lewis
21000 Brookpark Road
Cleveland, OH 44135

Dear Mr. Shaltens:

We enjoyed meeting with you on Wednesday, January 24, 1990. It looks like you have a lot of work to do in a short amount of time in preparing your report on the Stirling engine.

With respect to the requirements that vehicles equipped with Stirling engines may have to meet in the future, I strongly urge that you stress the moving baseline and the possible range of future requirements.

The Moving Baseline

The competition keeps improving. Cars powered by conventional engines keep getting more efficient and cleaner. The real test for alternatives to current powerplants is not whether they are projected to be better in some measure than today's or yesterday's vehicles, but whether they are projected to be better than today's engines are projected to be. This necessarily leads to some degree of speculation (projection versus projection), but it appears to me to be the fairest way to compare.

Range of Requirements

Today's fleet MPG standard is 27.5. Values in the low 30's are being discussed for the mid-1990's, and higher values are being considered for future years. My guess is that the requirements will range as follows:

Year	Effective MPG Requirement
1990	27.5
1995-97	27.5 to 35
2005	27.5 to 40
2015	27.5 to 50

The pros and cons of the Stirling may be different depending on which end of the range you consider.

I already sent you materials that will allow you to construct ranges for future exhaust emission requirements.

FEB 8 1990

Emission Durability

There are two jobs to accomplish before one can say that there is a high probability that any emission standard can be met: 1) low-mileage emission achievement and 2) durability demonstration. Meeting the level of an emission standard at low mileage is a necessary but not sufficient condition.

The data that I have seen so far from vehicles powered by Stirling engines are totally deficient with respect to any evaluation of evaporative emissions, either diurnal emissions or hot-soak losses. As you can tell from the information I sent you, emissions other than exhaust emissions are much more important than they used to be.

With respect to exhaust emissions, the scattered bits of data I have seen indicate that the emission levels measured at low mileage are about the same, maybe even somewhat higher than those measured from today's cars at low mileage. Please see the enclosed test car lists for the model years you requested for the details.

The biggest unknown is durability. Low emissions have to be maintained for the length of the durability requirement. If the requirement is for a passenger car the durability requirement is 50,000 miles. If the vehicle is a light-duty truck the requirement is much longer. I've used 120,000 miles in the example below. To remove variability, you really need to run multiple vehicles and have multiple tests at each test point (each 5,000 miles). A test costs about $2,000 and it can cost about $2 per mile to have the miles put on. You said that each test car would cost $500,000. For a three-vehicle program the costs are estimated below.

Costs to Run Durability
Three-Vehicle Program

	50K Durability	120K Durability
Vehicle cost	1500K	1500K
Mileage cost	300K	720K
Test cost	180K	432K
TOTAL	1980K	2652K

It looks to me like you need about 2 to 3 million dollars to get a handle on emission durability for a single well-defined package with low-emission potential.

I've included some information about recent air quality measurements. These data indicate what I told you in the meeting, that there is a substantial ozone and carbon monoxide air quality problem in the U.S.

Also included is SAE Paper 835023 by T. Weber. If you could send us a copy of the work you mentioned that NASA has done on hydraulic hybrids, we would certainly appreciate it.

Finally, while an efficient, clean low-power engine for a hybrid is quite attractive (the ghost of the Stirlec?) and the 250K value you cited is attractive as research equipment goes, it seems that the engine you have under development is solar-powered not combustion gas powered, as I understood you to say, and so doesn't fit in with our current plans. If you develop a propulsion system with hydraulic launch capability that could operate cleanly on alternate fuels, we would of course be more interested.

Good luck with your study. We would appreciate seeing a draft of it, at least the sections that deal with emissions. If Jack McFadden is assisting you with this, have him give me a call if he has any questions about the CFR booklets we've included.

Sincerely yours,

Karl H. Hellman

Karl H. Hellman, Chief
Control Technology and Applications Branch

Enclosures

cc: G. Piotrowski, CTAB (w/o enc)

6 MAR 1990

AMSTA-RSA

MEMORANDUM FOR: NASA Lewis Research Center, Stirling Technology Branch, Mail Stop 301-2, Mr. Richard Shaltens, 21000 Brook Park Rd., Cleveland, Ohio, 44135

SUBJECT: Summary of Infrared (IR) Testing of a Stirling Engine Pickup Truck

1. Subject testing was conducted at The U.S. Army Tank Automotive Command, Warren, MI on the morning of 6 Dec 1988. IR imagery was used to compare the signature of the Stirling pickup and a conventional V-8 Dodge D-150 pickup.

2. The Stirling pickup exhibited a much lower exterior signature during identical warmup and operational tests. Heating of the engine compartment exterior was greatly reduced for frontal, side, and top viewing. An example of this effect was the frontal left exterior reduction from 18.5 degrees Centigrade (C) on the V-8 pickup to 12.7 degrees C on the Stirling pickup. The exhaust pipe temperature was reduced from 66 degrees C to 22 degrees C from side viewing angles. Heating of the ground under the Stirling pickup was also significantly reduced.

3. Imagery of the open engine compartment areas on the two pickups provided the source of the external signature differences. The internal combustion engine had significant radiant heat losses from the exposed exhaust manifolds which were at a 285 degree C temperature. The maximum temperature of the Stirling engine exterior was 47 degree C, except for the a very small area above the ignitor which measured 285 degrees C, and the exhaust manifold was 45 degrees C.

3. In summary, the Stirling pickup exhibited much lower IR signature levels during testing. This appeared due to the high efficiency and low heat rejection levels of the engine compared to conventional pickup engines. The low IR signature of the engine would be ideal for applications in light wheeled vehicles for transport of forward observers. Signature suppression hardware could be used to reduce the IR signature to levels below conventionally powered wheeled vehicles. Another application would be in low signature auxiliary power units (APU's) for military applications. This type of engine could also be used in heavy combat vehicle applications to reduce inherent IR signature levels.

4. The POC on this test evaluation is Mr. Wally Mick, of the Applied Research Branch, AMSTA-RSA, telephone number 313-574-8911 or AV786-8911.

GRANT R. GERHART
C, Applied Research Br

JAN 3 1990

Mr. Leonard Ault
Acting Director, Technology Utilization
National Aeronautics and Space Administration
Washington, DC 20546-0001

Dear Mr. Ault:

I have read your letter regarding the commercialization study of Stirling Engine Technology requested by Congress and offer the following comments.

> Robert K. St. Francis, Director, Office of Fleet Management, U.S. Postal Service, is the Postal Service's representative for this study. He can speak for the Postal Service on this program.
>
> Approximately two years ago, the U.S. Postal Service was approached by NASA to participate in a demonstration project because of our unique vehicle operational environment. We in turn volunteered to participate in this program as a test bed or test platform and gather operational data pertaining to the performance of the vehicle with a stirling engine compared to that of a conventional spark ignited internal combustion engine. The preliminary results are available and our assessment shows that the engine performs less favorably than the original engine furnished with the vehicle. While I recognize that the stirling engine is in its development infancy for automotive application, I can not envision any potential long term benefits for the Postal Service or any large scale application to our fleet operation.

In response to the three points raised in your letter, the following responses are presented.

Point 1. Long term sponsor

Response: The mission of the Postal Service is to provide a uniform, universal delivery system to the nation. Our role is not to develop engine technology for future automotive applications. We would, as we have in the past, participate in a limited demonstration project if requested, providing it did not interfere with the efficiencies of our mail delivery system. We would not be a long term sponsor.

Point 2. Agency cost sharing

Response: The Postal Service would absorb the costs associated with a limited demonstration test as we presently have done, again with the proviso that the demonstration would not adversely effect our delivery capability.

Point 3. Agreement on the key study results and recommendations

Response: This is difficult for me to comment on because of the many technological variables involved. If the engine is operating, as I have been told, and producing less emissions in some areas and may be capable of running on many alternative fuels, can a concensus be reached that this is the ultimate engine for future automotive application? I do not think so. The engine technology (stirling) is in its modern day infancy even though the concept has been around a long time. For me to predict that an agreement be reached on a complex subject such as this is premature and should be determined by the deliberations of your study group. There exists a possibility that many differing opinions may come out of these deliberations, and all of them should be reported objectively to Congress.

If I can be of any further assistance, please feel free to contact me.

Sincerely,

/s/
Arthur Porwick
Assistant Postmaster General

UNITED STATES POSTAL SERVICE
475 L'Enfant Plaza, SW
Washington, DC 20260

FEB 21 1990

Mr. Len Ault
Director of Technology Utilization
National Aeronautics & Space Administration
Code CU
Washington, DC 20546-0001

Dear Mr. Ault:

The evaluation of the second generation automotive Stirling Engine (Mod II ASE) powered Long Life Vehicle (LLV) by the USPS was concluded on December 29, 1989. We appreciated the opportunity to participate in this evaluation. The Stirling Engine powered LLV arrived at the USPS Engineering & Development Center on September 29, 1989 and our evaluation continued for approximately three months.

We encountered various engine/accessory problems and a chase vehicle was needed throughout the evaluation period. As a result of these problems, it appears that this engine is still in the development prototype stage and is not ready for larger fleet deployment until the problems can be resolved and the chase vehicle can be eliminated.

EPA Urban Cycle Fuel Consumption Test results showed that the present GM 2.5L IC Engine LLV had a 3% to 4% better fuel economy than the Stirling Engine LLV. For the highway cycle, the Stirling Engine LLV had a 18% to 23% better fuel economy than the GM 2.5L IC Engine LLV. However, it should be noted that the USPS usage of this vehicle is very similar to the urban cycle. On the actual Postal delivery route, the Stirling powered LLV consumed 38.5% more fuel than the GM 2.5L IC Engine. Therefore, we conclude that the present Mod II Stirling Engine is not suitable for Postal operation.

A more detailed analysis of the performance of the vehicle is included in the "Stirling Engine Powered Long Life Vehicle Evaluation Program Final Report" which is attached.

If you have any question, please contact me at 268-3615 or John Bowen at 641-7130.

Robert St. Francis
Director
Office of Fleet Management

cc: Albert Chesnes, Department of Energy
Albert Ritchey, MTI

APPENDIX I

STIRLING COMMERCIALIZATION STUDY: INTERAGENCY PARTICIPATION

In response to House Report 101-226 accompanying HB 1759, the National Aeronautics and Space Administration Multiyear Authorization Act of 1989, NASA Headquarters, Office for Commercial Programs, Washington, DC, requested the NASA Lewis Research Center, Cleveland, Ohio, because of their extensive research efforts in support of the automotive Stirling engine technology, to take the lead in conducting the study for Congress.

The report language directed NASA to request participation from other Federal agencies and encouraged NASA to consult with the private sector. An interagency study team was formed as requested and the private sector was consulted.
The first meeting of the interagency study team was held on December 7, 1989, in Washington, DC. Agencies represented in addition to NASA were the Department of Energy, the Department of Transportation, the Environmental Protection Agency, the United States Air Force, and the United States Postal Service. At this meeting NASA reviewed with the attendees the congressional report language directing the study, the background and status of the DOE Automotive Stirling Engine (ASE) Program, the background on Stirling engines, and a plan to respond to Congress. Potential areas of participation were also reviewed and discussed with the various agencies. A second meeting of the interagency study team was held on January 4, 1990, in Washington, DC. Areas of expertise and participation were discussed with the agencies, and key areas of participation were identified for each agency as follows:

DOE
- Potential energy benefits
- ASE program assessment
- Past fleet demonstration experience
- Alternative fuels projections
- Future energy assessment
- Future engine projections

EPA
- Potential and current emission benefits

- Current emissions standards and engine capability
- Future emissions standards and engine capability

DOT

- Potential urban mass transport benefits
- Past fleet demonstration experience

NASA

- Lead for interagency study
- Stirling technology assessment
- Consultation with private sector
- Other duties as required

Air Force, Army, and USPS

- Potential benefits
- Recommendation of demonstration fleet
- Stirling demonstration results

Further potential Stirling benefits for the automotive application were reviewed and discussed with personnel from the attending agencies. Each agency was requested to provide written comments reflecting its input in its areas of expertise.

In consulting with the private sector, visits were made and discussions held with key personnel familiar with the DOE ASE program from the following industry organizations, who were:

1. Cummins Engine Company, Columbus, Indiana
2. Deere & Company, Moline, Illinois
3. Ford Motor Company, Dearborn, Michigan
4. Gas Research Institute, Chicago, Illinois
5. General Motors Research Laboratories, Warren, Michigan
6. Hercules Engine Incorporated, Canton, Ohio
7. Kennedy Engine Company, Biloxi, Mississippi
8. Stirling Thermal Motors, Inc., Ann Arbor, Michigan

Each organization was sent 10 "Questions for Industry" (attachment 1) prior to the visit to serve as a basis for discussing potential Stirling commercialization efforts. Written responses were received from all the organizations except Hercules and Stirling Thermal Motors. A visit was also made to the EPA, Ann Arbor, Michigan, for an in-depth review and discussion of both current and future automotive emissions standards.

In addition, a visit was made to the DOE ASE program contractor (Mechanical Technology Inc., Latham, New York) to obtain the current status of the NASA ASE project. MTI was very cooperative throughout the study and has provided the necessary information and data to NASA when requested.

NASA has prepared the Stirling commercialization study report based on the following:

1. Discussions with the industry organizations and their written responses
2. Discussions with the interagency participants and their written responses in their areas of expertise

Attachment 1

Questions for Industry

1. What advantages do you see for the Stirling engine that make it attractive to you as a manufacturer?
2. What are the disadvantages or shortcomings of Stirling that might discourage you from manufacturing Stirling engines?
3. What technology barriers do you believe exist for the Stirling?
4. What are the market needs for a new type of engine such as Stirling?
5. What market barriers exist for a new type of engine such as Stirling?
6. What do you see as the initial application(s) and market(s) for the Stirling engine?
    - Application(s) and engine size(s)?
    - Initial market sizes and initial engine cost?
    - Initial production run and mature engine cost?
    - How many years before mature market production? Annual production?
7. Describe a demonstration program that you would require before entering into initial production of a new type of engine such as Stirling?
    - Number of engines?
    - Type of testing?
        - Component and system performance
        - Endurance or life and reliability
        - In-service evaluations
8. What is your estimate (timetable) to bring a new engine such as Stirling into production?

    _______ years for the design and development?

    _______ years to demonstrate performance? endurance? _____ size?

    _______ years for in-service evaluations? ______ size?

    _______ years to initial production? ______ size? Plant cost?

    _______ years to mature production? _____ size? Plant cost?
9. What is government's role in the commercialization of a new engine such as Stirling? Why?
10. Considering the advantages attributed to Stirling and the progress made in advancing Stirling technology, why has industry not been interested in pursuing it?

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of

L:HR:jl

JUN 20 1990

Honorable Robert A. Roe
Chairman
Committee on Science,
  Space and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

In its Report (House Report 101-226) accompanying H.R. 1759, the National Aeronautics and Space Administration (NASA) Multiyear Authorization Act of 1989, the House Committee on Science, Space and Technology requested that NASA provide an annual report to the Committee addressing management at the Space Station Freedom Program Office in Reston, Virginia. In response to the Committee's request, this report addresses staffing levels (both civil service and contractor), use of Reston contractors, interfaces/controls with other elements of the program, and the impact of personnel levels upon scheduled accomplishment of work.

Please let me know if you require any further information in this regard.

Sincerely,

Martin P. Kress

Martin P. Kress
(Acting) Assistant Administrator
for Legislative Affairs

Enclosure

cc: Honorable Robert Walker

SPACE STATION LEVEL II MANAGEMENT AND INTEGRATION STATUS

Submitted to the

Committee on Science, Space and Technology
U.S. House of Representatives

OFFICE OF SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

JUNE 1990

SPACE STATION LEVEL II MANAGEMENT AND INTEGRATION STATUS

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I. INTRODUCTION

The following report is submitted in response to a request from the Committee on Science, Space and Technology, U.S. House of Representatives, in Report 101-226. This report, dated August 31, 1989, requests that NASA provide information on the management situation in Reston, including staffing levels (both civil service and contractor), use of Reston contractors, interfaces/controls with other elements of the program, and any work that is not being accomplished because of personnel shortages.

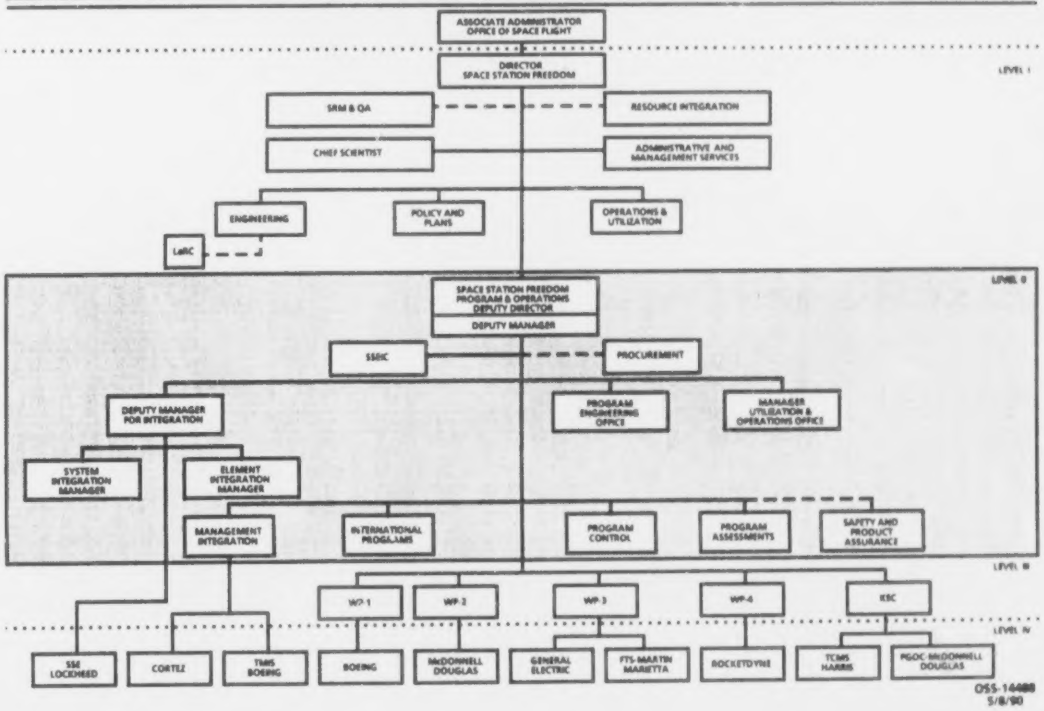
II. SPACE STATION FREEDOM MANAGEMENT ORGANIZATION

Space Station Freedom is a large, multipurpose, permanently manned orbital facility with many diverse requirements. To maximize the benefits that the station will offer in terms of scientific research, technology development, space applications and space exploration, it is necessary to balance current and potential requirements, user needs, operational factors and both near-term and long-term costs. This balance poses a major challenge for program management and integration.

The management approach in place for the station allows the program to utilize the diverse capabilities of the NASA Centers as well as the expertise of a broad range of U.S. aerospace firms. While Kennedy Space Center (KSC) provides for the launch processing and launch of the Space Station flight elements by the Shuttle, hardware and software design and development efforts have been divided into four work packages, each assigned to a NASA center. Marshall Space Flight Center (MSFC), Johnson Space Center (JSC), Goddard Space Flight Center (GSFC), and Lewis Research Center (LeRC) each has a prime contractor which, with its subcontractor team, carries out the center's project development responsibilities. In addition, each center has local supporting development contractors and operations contractors. The activities of the four work packages are interrelated and involve multiple interfaces within the total Space Station Freedom system. In addition, the Space Station management must integrate the activities of the three international partners: European Space Agency (ESA), Japan and Canada.

Since the last report to the Congress on Space Station Management and Integration, two significant changes have occurred. The Space Station Program and Space Shuttle Program have been combined into the Office of Space Flight, and the program integration responsibilities at Level II have been geographically distributed to the JSC and MSFC. The organization for Space Station program management is attached. This chart shows the same four tier organization that has been in place since the inception of the program and which was the framework for last year's report. Level I provides overall program direction and policy, Level II provides day-to-day management and overall system engineering and integration. The Level III field center project offices direct the design and development of the hardware and software, which is performed by the prime/subcontractor teams at Level IV.

SPACE STATION FREEDOM PROGRAM OFFICE



ASSOCIATE ADMINISTRATOR OFFICE OF SPACE FLIGHT

LEVEL I

DIRECTOR SPACE STATION FREEDOM

SRM & QA

RESOURCE INTEGRATION

CHIEF SCIENTIST

ADMINISTRATIVE AND MANAGEMENT SERVICES

ENGINEERING

LeRC

POLICY AND PLANS

OPERATIONS & UTILIZATION

LEVEL II

SPACE STATION FREEDOM PROGRAM & OPERATIONS DEPUTY DIRECTOR

DEPUTY MANAGER

SSEIC

PROCUREMENT

DEPUTY MANAGER FOR INTEGRATION

PROGRAM ENGINEERING OFFICE

MANAGER UTILIZATION & OPERATIONS OFFICE

SYSTEM INTEGRATION MANAGER

ELEMENT INTEGRATION MANAGER

MANAGEMENT INTEGRATION

INTERNATIONAL PROGRAMS

PROGRAM CONTROL

PROGRAM ASSESSMENTS

SAFETY AND PRODUCT ASSURANCE

LEVEL III

WP-1

WP-2

WP-3

WP-4

KSC

LEVEL IV

SSE LOCKHEED

CORTEZ

TMIS BOEING

BOEING

McDONNELL DOUGLAS

GENERAL ELECTRIC

FTS-MARTIN MARIETTA

ROCKETDYNE

TCMS HARRIS

PGOC-McDONNELL DOUGLAS

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A number of efficiencies have been realized by combining the Shuttle and Freedom Programs, and an experienced space flight team has been put in place. Since the Space Station will be launched using the Shuttle and assembled on-orbit, combining the two programs under a single Associate Administrator for Space Flight has improved communications and the decision process in several key areas, including the assembly sequence and Space Shuttle/Space Station interfaces. In addition, the astronauts who will assemble and operate the Station have a more direct influence on its design.

Changes were also initiated last year in the management at Level II (which are the primary focus of this report) that will bring greater manned space flight experience into the management team. These changes will be discussed in the following sections.

III. LEVEL II FUNCTIONS AND RESPONSIBILITIES

The Space Station Freedom organization at Level II is under the direction of the Deputy Director, Programs and Operations. He is responsible for overall day-to-day program management, system engineering and integration and program control. He executes the hardware and software development activities through the five Level III project managers at JSC, MSFC, GSFC, LeRC and KSC. He executes the overall program system engineering and integration activities through a Manager for Program Integration and a Manager for Program Engineering. Utilization and operations planning and capability development are directed through a Manager for Utilization and Operations.

This organization is similar to the Level I/II relationships in the Space Shuttle program. Overall direction is provided by the Director at Level I, while day-to-day implementation is under a Deputy at Level II.

Overall Program Management and Control

As has been discussed in previous reports, the program management and program control function at Level II encompasses the "normal" program management functions related to the integrating contractor role. Following the Challenger accident, the NASA Administrator asked General Sam Phillips, former Apollo Program Director, to head a management committee to examine Space Station program management. The Phillips Committee recommended a centralized management approach located in Washington, D.C., having overall system engineering and system integration responsibilities similar to those of the Apollo Program Office in the 1960's which managed the highly successful Apollo Program.

To carry out its responsibilities for program engineering, integration and operations, the Level II Program Office utilizes three major contracts: the Space Station Engineering and Integration Contract (SSEIC), the Software Support Environment (SSE) contract, the Technical and Management Information System (TMIS) contract. SSEIC is the integrating contractor through which Grumman, with its subcontractors, has major responsibilities in program engineering and integration, operations and utilization, program control and management, information systems, operations, program requirements and assessment, utilization, safety, reliability, quality assurance and international programs integration. SSEIC also develops test requirements for verification, assembly and overall integration of space station flight elements.

The Software Support Environment (SSE), contract under Lockheed, was created to provide the rules and tools needed for software development and life cycle maintenance. SSE produces the necessary software to turn a host of computers into a Space Station Freedom Program Software Development Facility. These are put into place at the work package centers and at selected contractors. This standardization will result in major software life cycle cost savings and minimize the cost and risk traditionally associated with large, complex software development efforts by providing complete and consistent support for the development and maintenance of mission software. The support environment consists of several components: software engineering tools, software development rules and procedures, operating system interfaces, and software standards.

The Technical and Management Information System (TMIS), contract under Boeing, is a computerized system which provides program-wide applications data bases for the acquisition, organization, storage and transfer of vast amounts of technical and management data in order to maximize effectiveness and efficiency. The system is designed to handle a continuous stream of data and maintain its usability over the lifetime of the station. In order to increase the cost effectiveness of the station's design, development and operations, TMIS supports integration of engineering design data bases, requirement documents, cost data, payload/accommodation data, planning data and schedules. In addition, TMIS provides hardware, standards and applications to all NASA participants to facilitate the creation of a program wide data base. Technical and business data bases can be accessed by any program participant requiring the information.

The Cortez contract provides general administrative support to Level II (i.e., grounds security, building maintenance, graphics support, etc.)

These Level II contractor teams provide the SSFPO supporting infrastructure and expertise to carry out its management and program integration functions.

Overall Program Engineering and Integration (PEI)

The primary objectives of Level II program engineering and integration are definition of the program requirements, system engineering of the top-level design to assure design cycle convergence, conduct of major design reviews, development of the interface definition and development activities between the systems and elements which comprise the manned base, including those of the international partners.

The development of program requirements has been underway for several years and the requirements are reaching a reasonably mature state. However, there are still significant design trade-offs that must be made in FY 1990 as the program approaches Preliminary Design Review (PDR) to assure that the preliminary design converges to meet the requirements. Where there are significant disparities between the design solution and the requirement, either the requirement must be changed because it is perhaps unrealistic or the design must be modified to meet the requirement. It is this interactive process that requires Level II program engineering and integration to find cost-effective ways of resolving the issues which may arise.

In order to successfully complete the Program PDR, Level II program engineering and integration must participate in the approximately 80 incremental preliminary design reviews on Space Station elements and systems to assess and evaluate the design against the Level II requirements. The Program PDR will focus on two representative stages of assembly: Permanently Manned Capability and Assembly Complete. However, an evaluation of the intermediate stages of assembly is required to assure the viability of the completed station. The stage definition and performance assessment is a major engineering and design integration task in FY 1990 in preparation for the Program PDR.

As referenced earlier in this report, the program integration activities have been transferred to Level II offices for system and element integration at JSC and MSFC, respectively. The primary thrust of this activity in FY 1990 is to update the Architectural Control Documents (ACDs), to define the Interface Control Documents that will be needed as the designs progress from preliminary to detailed design and the Baseline Configuration Documents that define physical location of hardware on the station. System integration is to be located at JSC and element integration will be accomplished at the MSFC where there is a broad base of experience in manned spaceflight in the NASA institution as well as the industrial community located nearby.

The NASA civil servants will manage the activities of the integrating contractor, SSEIC, as well as integration activities delegated to the prime contractors.

Ground Systems Engineering and Integration

Another essential Level II program engineering management and integration function is the planning and implementation of the ground systems and facilities required to support the flight system. These systems must be in place about two years prior to First Element Launch to support training of the flight crews and ground teams needed to begin initial operations. The major thrust in FY 1990 is to complete definition of the requirements and document them in Functional Control Documents (FCD). These FCDs will define the architecture and interfaces for the ground systems in much the same way as the ACDs define the architecture and interfaces for the flight systems.

User Integration

Level II's user integration activity provides the scientific and industrial user communities access to a space facility that is user-friendly and that provides a variety of capabilities for research in the space environment. Since the lead time for experiment developers is sometimes as long as for the Space Station itself, it is essential that planning be underway now to meet the user integration needs beginning in the mid-1990's. The manager for Utilization and Operations and his staff work closely with representatives of the NASA user codes on these user integration activities, and the user codes are members of the Space Station Control Board chaired by the Deputy Director, Program and Operations.

IV. STAFFING

The consolidation of the program integration functions under a single Level II Manager for Program Integration with managers co-located at JSC and MSFC will greatly strengthen this activity. It will also place the integration function closer to where the design work is being done, so that the system and element integration team will be able to more effectively utilize the resources and technical talent which resides at these field centers.

We are planning to have 206 civil servants at Reston by the end of FY 1990. By the end of the year, there will be approximately 50 civil servants supporting program integration at MSFC and JSC.

There are approximately 1250 contractor employees currently assigned to the program engineering and integration activity: Boeing has approximately 250 employees under the TMIS contract which should remain constant over the next few years; slightly over 700 Grumman employees under SSEIC which is projected to increase over the next few years; and approximately 300 Lockheed employees under the SSE contract.

We also plan to build up the program wide integration activities in FY 1990-1995 utilizing the prime contracts, McDonnell Douglas at JSC and Boeing at MSFC, in addition to the SSEIC Grumman contract. This activity will build up to approximately 550 contractor employees.

The Preliminary Design Review will be completed at the beginning of FY 1991 and the program will move on the detailed design and development activities in FY 1991 to prepare for the Critical Design Reviews. By FY 1992, large-scale fabrication and testing of flight hardware will commence and continue for several years. Adhering to this schedule is necessary to begin assembly in orbit in early 1995, establish permanently manned capability by mid-1997 and to complete the baseline Space Station by mid-1999, and requires adequate manpower resources at Level II and all other parts of the program.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

14 1990

Honorable Robert A. Roe
Chairman
Committee on Science,
  Space and Technology
House of Representatives
Washington, DC 20515

JUN 14 1990
and Technology

Dear Mr. Chairman:

In accordance with H.R. 3729, the National Aeronautics and Space Administration Multiyear Authorization Act of 1989, Section 4(2)(c), as passed by the Senate, on November 22, 1989, NASA is submitting the following information on the anticipated schedule for block changes in the Tracking and Data Relay Satellite System (TDRSS) and the launch of these spacecraft on Expendable Launch Vehicles (ELVs).

The Tracking and Data Relay Satellite (TDRS) baseline program includes TDRS-7 and TDRS-8. Construction was initiated in FY 1987 on TDRS-7, the replacement spacecraft for TDRS-2 that was lost in the Challenger accident. Long lead parts are currently being procured for TDRS-8, with start of construction planned in late 1991. TDRS-8 will be the last of the current spacecraft design and will provide for critical requirements of the TDRSS. Both TDRS-7 and TDRS-8 are baselined to be launched on the Space Shuttle in April 1995 and September 1995, respectively.

The design changes that will make the spacecraft compatible with launch on ELVs are scheduled to occur with the advent of the Advanced TDRSS (ATDRSS) program. The procurement for ATDRSS directs the contractors to design the spacecraft for an ELV launch. In addition, the contractors have been requested to provide information which will allow NASA to assess the desirability of contracting not only for the spacecraft but also for the launch services, so that the contract will provide for delivery of the spacecraft to NASA on orbit.

NASA has completed Phase A of the ATDRSS program and is reviewing the Phase B proposals. To ensure the availability of the initial ATDRSS spacecraft no later than 1997, we intend to commence the Phase B study activities in June of this year instead of October. This will not increase the FY 1990 budgetary requirements for the Space Operations program.

Based on our thorough review of the ATDRSS program, and the schedule risks associated with a new spacecraft design, we have concluded that it would be imprudent to forego construction of TDRS-8 in the hope that the development schedule for the ATDRSS could be accelerated. The 1995 manifest launch date for TDRS-8 represents our current best assessment of its need date. We believe that the first ATDRSS should be planned for availability no later than 1997. In our view, this represents a balanced approach to minimizing service support risks during the transition to the next generation of tracking and data relay spacecraft.

If you would like to meet to discuss this program in greater detail, I am available at your convenience.

Sincerely,

James R. Thompson

James R. Thompson, Jr.
Deputy Administrator

cc:
Honorable Robert Walker

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: L:VJS:brb

JUL 31 1990

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed is a report on Expendable Launch Vehicles (ELV) technologies prepared in response to the Commercial Space Launch Act Amendments of 1988, P.L. 100-657. We apologize for the lengthy period which has been required to develop this report, but hope this material will be useful to the Committee as this important issue continues to be discussed.

Please feel free to contact us if the Committee requires any further information on this subject.

Sincerely,

Martin P. Kress

Martin P. Kress
Acting Assistant Administrator
for Legislative Affairs

Enclosure

cc: Honorable Robert S. Walker

National
Aeronautics and
Space
Administration

EXPENDABLE LAUNCH VEHICLES TECHNOLOGY REPORT

Report for the
Subcommittee on Science, Technology and Space
of the
Committee on Commerce, Science and Transportation
UNITED STATES SENATE

And the

Subcommittee on Space Science and Applications
of the
Committee on Science, Space and Technology
U.S. HOUSE of REPRESENTATIVES

Office of Aeronautics, Exploration and Technology
and
Office of Space Flight
NASA Headquarters

July 1990

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SUMMARY

As directed in Public Law 100-657, "Commercial Space Launch Act Amendments of 1988," and consistent with National Space Policy, NASA has prepared a report on a potential program of research on technologies to reduce the initial and recurring costs, increase reliability, and improve performance of expendable launch vehicles for the launch of commercial and government spacecraft into orbit.

The report has been developed in consultation with industry and in recognition of relevant ongoing and planned NASA and DOD technology programs which will provide much of the required launch systems technology for U.S. Government needs. The report identifies additional efforts which could be undertaken to strengthen the technology base. To this end, the report is focused on needs for launch vehicle technology development and, in selected areas, includes verification to permit private-sector new technology application at reduced risk. If such a program were to be implemented, it would entail both government and private-sector effort and resources.

The additional efforts identified in the report would augment and not replace, the existing launch vehicle technology programs. The additional efforts identified in the report have not been funded, based upon agency assessments of relative priority vis-a-vis the existing programs. Throughout the consultation and review process, the industry representatives stressed the overriding importance of continuing the DOD/NASA Advanced Launch Development (ALD) activity and other government technology programs as a primary source of essential launch vehicle technology.

I BACKGROUND AND INTRODUCTION

Section 10 of Public Law 100-657, "Commercial Space Launch Act Amendments of 1988," directed that NASA, "in consultation with representatives of the space launch and satellite industry, design a program for the support of research into launch systems component technologies, for the purpose of developing higher performance and lower cost United States launch vehicle technologies and systems available for the launch of commercial and Government spacecraft into orbit."

The accompanying committee reports state that a major purpose of the legislation is "to ensure the successful development of a competitive domestic expendable launch vehicle (ELV) industry." They stress the importance of the industry to national space efforts and to continued U.S. aerospace preeminence. They also state the belief that a continuing research and development program in launch vehicle technologies will be beneficial to government and commercial operators and is essential to the maintenance of a competitive domestic launch industry. The reports cite NASA's aeronautics research and technology program as a model for the desired long-term program in launch vehicles.

In addition to technology, P.L. 100-657 addresses a number of other issues affecting commercial launch activities, including private acquisition of government property and services, liability insurance, scheduling of government and commercial payloads on commercial launch vehicles at government launch sites, and fairness in commercial space international competition. This NASA report, however, is confined to the research and technology (R&T) question put forth in Section 10. Appendix A reviews progress on several policy and administrative actions relative to suggestions by Department of Transportation's (DOT) Commercial Space Transportation Advisory Committee (COMSTAC). As in the aeronautics model, systems development by either industry or government entails far greater investment than does R&T. The availability of proven technology does not eliminate the need for large development investment. However, it reduces the development risk and increases the likelihood of success.

This report has been developed in consultation with appropriate representatives of industry, DOD, and other involved government agencies. The primary emphasis is on ELV technology for major system cost reductions as well as improvements in performance, reliability, and launch operations economy. It includes consideration of transfer vehicles required to deliver payloads to geosynchronous or geostationary orbits. If approved, the program would complement--not duplicate or replace--related NASA and Air Force ongoing or planned activities.

II ELV OVERVIEW

This overview is provided as a review of the commercial ELV industry evolution and the government/industry relationships which affect the application of new technology to current and future ELV developments.

The National Space Policy announced by the President in November 1989 sought to encourage development of the commercial launch industry by directing U.S. government agencies to: make national ELV properties and services available to the commercial sector on a reimbursable basis; avoid government competition with commercial launch providers; require the use of commercial space transportation services for government programs to the maximum extent feasible; promote international free and fair trade practices; and support research and development for future space transportation.

The post-Apollo space developments which preceded establishment of the National Space Policy included a number of changes in launch vehicle strategies. In the late 1970s a decision was made to phase out ELVs and rely solely on the Space Shuttle for launch capability. By 1983 the transition was nearly complete; the government ceased ELV procurement and the launch vehicle manufacturers discontinued ELV research, development, and production. However, subsequent policy decisions and legislation have restored the ELV as a significant component of the national launch capability.

In 1985, Congress approved the Complementary ELV (CELV) program in 1985 to provide an alternative to the Shuttle for high-priority military payloads and also authorized conversion of decommissioned Titan II ICBMs for use as space launch vehicles. Martin Marietta won the CELV competition with the Titan IV and was also awarded a contract to modify Titan IIs.

In the aftermath of the 1986 Challenger and Titan 34D accidents, a reassessment of national space transportation needs led to establishment of a mixed fleet launch strategy (Space Shuttle and ELVs) to support both military and civil government missions. Commercial payloads not requiring the unique capabilities of the Shuttle were removed from the manifest. The DOD expanded the Titan IV program to accommodate critical payloads off-loaded from the Shuttle. In 1987 McDonnell Douglas was awarded the Air Force Medium Launch Vehicle (MLV) contract for Delta II vehicles to support the launch of Global Positioning Satellites (GPS). The MLV II was awarded to General Dynamics in 1988 for Atlas II vehicles to support Defense Satellite Communications Systems (DSCS) launches.

A NASA space transportation study conducted after the Challenger accident concluded that a robust and balanced mixed fleet is necessary for resilient U.S. civil space operations, increased access to space, and enhanced mission flexibility. The NASA mixed fleet launch strategy, established in 1987, seeks to ensure the availability of a range of ELVs to complement the unique attributes of the Shuttle for approved civil government missions. NASA rescheduled to ELVs four Shuttle payloads that were displaced or would have faced lengthy delays after the Shuttle's return to flight. In 1988 NASA awarded the U.S. government's first commercial ELV launch services contract to General Dynamics to support the launch of NOAA Geostationary Operational Environmental Satellites (GOES).

By current national policy directives, NASA is precluded from maintaining an ELV adjunct to the Space Shuttle Program and is further directed to purchase launch services from the private sector to the maximum extent feasible or through the DOD. NASA is procuring commercial launch services competitively in three launch vehicle performance classes: SELV (small ELV -- e.g., Scout); MELV (medium ELV -- e.g., Delta II); and IELV (intermediate ELV -- e.g., Atlas I/II, Titan III). Large ELV class (e.g., Titan IV) vehicles are not presently available commercially and will be procured through the Air Force.

Additional details regarding these Air Force and NASA ELV procurements, and brief descriptions of the vehicles, are contained in Appendix B.

Most of the commercial launch vehicles being produced and marketed by General Dynamics, Martin Marietta, and McDonnell Douglas are variants of the government-developed space launch vehicles. They are being marketed for sale to the U.S. government as well as to domestic and international commercial customers. Each corporation has made substantial corporate investments in its commercial product lines, using available technology to modernize vehicle systems, manufacturing facilities, and launch facilities. However, no major new system developments independent of government launch requirements have been undertaken or announced.

A number of new small ELVs are being developed with private capital to compete with the government-developed Scout launch vehicle. The NASA Scout, a four-stage solid-propellant booster developed in the 1960s to support NASA and DOD small-payload launches, has completed well over 100 launches. Over the past 20 years, it has maintained a 98% reliability. LTV Missiles and Electronics plans to market the Scout commercially. The American Rocket Company, Orbital Sciences Corporation, and Space Services Inc. are among the domestic entrepreneurial companies entering the market for small-class orbital and sub-orbital launches.

Some market projections, including the Department of Commerce's May 1988 report "Space Commerce -- An Industry Assessment", estimate the ELV market demand through the remainder of this century to include between 150 and 250 U.S. and foreign commercial launches involving payloads of 4000 lbs. or more to low earth orbit, and approximately twice that total in the smaller orbital and sub-orbital classes. However, these projections have not yet materialized. In addition to the projected multi-billion-dollar commercial launch services market, Commerce also projects a large associated demand for launch support (e.g., payload processing) operations. One private domestic company, AstroTech, Inc., is currently engaged in providing such services for commercial payload launches.

U.S. manufacturers seeking commercial launch business face serious competition from foreign ELVs -- principally the European Ariane family of vehicles, China's Long March series, the Soviet Union's Proton, and a developing new family of Japanese vehicles. The competing foreign vehicles are not necessarily more advanced technologically, and in most instances they have not yet established success rates comparable to those of the U.S. vehicles. Some of them, however, incorporate state-of-the-art technology and have been designed specifically for delivering payloads to orbit rather than derived from missiles designed to more costly military specifications. They operate, or will operate, from government bases which are well suited for commercial use, at locations which may offer appreciable performance advantages because of more favorable latitudes relative to U.S. launch sites. In short, the foreign launch vehicle companies and their governments are strong competitors now and will be even more formidable in the near future.

In general, the technology being developed in U.S. government research programs for improvement of launch economy, reliability, and performance is relevant both to the government's continuing requirement for economical civil and military launch services and a competitive domestic launch vehicle industry.

III REVIEW PROCESS

A review team consisting of NASA Headquarters and Center specialists in each of the relevant technical disciplines reviewed ongoing and planned NASA technology programs to identify elements which provide significant ELV technology contributions, and to identify areas in which additional effort could increase the benefits to ELV development. These programs included the Office of Aeronautics, Exploration and Technology (OAET) R&T Base programs in both space and aeronautics, the Civil Space Technology Initiative (CSTI) and Exploration Technology programs, and the Office of Space Flight (OSF) advanced development activities. The team similarly reviewed the Air Force/NASA Advanced Launch Systems (ALS) Advanced Development program, the National AeroSpace Plane (NASP) program, and existing ELV procurement and development plans. These reviews of ongoing technology programs, an assessment of the ELV technology environment and technology needs, and consultations with the ELV industry and the Air Force formed the basis for the potential ELV program described in this report.

Industry inputs were obtained through several mechanisms. Meetings were held with an Ad Hoc Review Team on Low-Cost ELV Technology organized under the NASA Advisory Committee's Space Systems Technology Advisory Committee (SSTAC) structure, the Secretary of Transportation's Commercial Space Transportation Advisory Committee (COMSTAC), and the Space Committee of the Aerospace Industries Association (AIA). The Ad Hoc Review Team also received Air Force briefings on relevant ALS technology issues. Additional insight on industry technology needs was obtained during discussions and reviews of Independent R&D activities at major ELV manufacturing and launch facilities.

A draft version of the ELV technology report was presented to each of the committees for review and discussion prior to final draft completion. In addition to the committee interactions, informal meetings and discussions involving individual members of the planning team and industry counterparts provided exchange opportunities during the review period. The draft report was reviewed and coordinated with the Air Force ALS Office, other offices within the Air Force Space Systems Division, and related Air Force and DOD offices in Washington.

IV ELV TECHNOLOGY ENVIRONMENT

Definition of the R&T needs addressed in the ELV report was based in part on the following observations developed in discussions with the ELV industry representatives:

- ELVs will figure prominently in U.S. and world space launch activities not only in the near future, but throughout and beyond the era of the new launch vehicles to be developed utilizing ALS or equivalent technology.

- In general, commercial launch vehicle manufacturers indicate that they are primarily absorbed with near-term orders and survival. They understand that their long-range future success will require continuing technology advancement for competitive cost, performance, and reliability. However, for the present, they indicate that realistic cost, risk, and time considerations limit their ability to incorporate new technology in ongoing commercial production of existing ELVs.

- Incorporation of new technology in modifications or derivatives of existing ELVs could result in appreciable cost reduction, although probably not to a level competitive with totally new systems optimized for low-cost commercial applications.

- Strictly from the standpoint of ELV technology needs, commercial vehicles do not present unique requirements. Differences between commercial and government launch vehicle development approaches and operations, however, may create new requirements with respect to technology validation, transfer, and application.

- The "aeronautics model" has not been directly applicable as an example for NASA support to previous (government-procured) space systems. With respect to its possible application to commercial launch vehicle development, some significant differences are apparent:

    - NASA does not develop aircraft, nor does it have primary mission responsibility for aircraft operations. NASA generates aeronautical technology solely for use by the industry or by DOD and other government agencies. For these reasons, and because U.S. industry bears the full cost of commercial aircraft development, NASA and industry cooperatively pursue the development of selected critical high-payoff, high-risk technologies through large-scale test validation to assure readiness for application.

- Relative to space systems including launch vehicles, NASA's mission does involve development and operation. NASA program offices have in many instances completed the necessary validation of technology as part of their systems development activity. NASA has initiated the CSTI and Exploration Technology programs, which include more focused space technology development and validation effort in areas related to future NASA missions. With respect to commercial development, although the mechanisms for introducing new ELV technology are still evolving, the industry representatives identified the lack of technology validation as an obstacle to successful industrial development of future commercial launch vehicles.

- Ongoing and planned NASA space R&T programs include considerable research on fundamental technologies, methodologies, and computational codes in all of the technical disciplines critical to advanced launch systems development. This research is applicable to expendable as well as reusable vehicles, but does not in the industry's view fully resolve the need for validation of new technologies specifically directed at low-cost ELVs, including the small vehicle category.

- The Joint DOD/NASA ALD (Advanced Launch Development) program will provide a strong base of available technology for development of new government and commercial ELVs applicable to a family of launch vehicles.

- Additional research and technology effort can be identified to go beyond the ongoing and currently planned programs by broadening the focus on longer-range future ELV developments, commercial operations, and smaller payload classes. In view of the likelihood that the larger ELV developments will for many years remain closely associated with government launch requirements, the planning of such additional effort should be thoroughly coordinated with the planning of related NASA and Air Force R&T programs directed at lower-cost and improved responsiveness to national space transportation needs.

- Although technology development and validation can significantly reduce development risk, some industry representatives express the view that, in its present state of early evolution, the commercial launch vehicle industry may have difficulty accepting the risk of incorporating even validated new technology in commercially funded developments.

- Finally, although NASA and industry technologists involved in major NASA space programs have established and maintained close working relationships, the commercial ELV industry is only beginning to recognize the benefits of continual exchange, consultation, facilities usage, and joint projects which characterize successful aircraft industry relationships with respect to aeronautical R&T. The difference can be attributed to the primarily military nature of the early ELV developments, the ELV R&D hiatus beginning in the late 1970s, the much more recent emergence of a commercial industrial sector, and the greater breadth of ongoing government and industry R&T programs in aeronautics. The development of closer relationships along the lines of the aeronautics pattern could benefit both the industry and NASA in the development and application of ELV technology.

V ELV TECHNOLOGY ASSESSMENT

A. OVERVIEW

The ELV technology assessment resulted in the outline of a set of activities which, if conducted in addition to the existing NASA and Air Force programs, would strengthen the technology base being developed to reduce launch vehicle cost and improve performance and reliability. In addition, it could reduce the risk of applying new technologies in government and commercial development. In the following sections the existing programs relevant to each technology discipline are discussed. Where additional effort has been recommended, the potential activity, and the benefits to be obtained, are summarized.

The DOD/NASA ALD program is the government activity which most directly affects the state of ELV technology for the next decade or two. ALD is a joint DOD/NASA program to define concepts and develop technologies applicable to a family of unmanned launch vehicles. This report is based on the best available current information as to ALS program content, and may require revision as that program evolves. NASA's close working relationship with the Air Force assures the ability to adjust promptly if necessary.

As suggested in Section IV, the technologies needed for commercial and government ELVs are very similar, but the industry representatives stressed that the risk of incorporating unproven technology may be prohibitive in commercial systems development. For this reason, and because of the government's increasing reliance on commercial launch services, the potential ELV program includes technology development and, in some instances, validation of critical high-risk technology. If the additional activities were to be implemented, this would require cooperative effort, and resources, on the part of the government and the private sector.

The current space transportation technology programs include considerable effort directed at advanced launch vehicles in general and hence are of value to ELVs. In some areas, the funding of potentially beneficial advances has necessarily been limited because of higher-priority requirements on resources. In preparation of the ELV technology report, activities previously judged to be of lower priority were considered for increased emphasis only where the R&T appeared significantly more important when viewed from the ELV perspective. Fundamental research and technology activities such as magnetoplasmadynamic propulsion and photonics have been retained in the base research and technology programs and have not been included in the potential ELV program.

Cost reduction is a primary objective of this examination of ELV technology, and is a major discriminator in establishing research priorities. Office of Space Flight statistics indicate that propulsion, materials and structures, and avionics and operations represent the three technology areas which account for the major percentage of ELV costs, and that the proportions of cost attributable to each of these three technology areas are roughly equal. In identifying R&T needs, equal attention was devoted to each of the areas.

Establishment of specific priorities requires detailed understanding of both the cost impact of individual technology improvements and the associated technology verification. To this end, and as means of evaluating the results of the technology development efforts, the potential program contains a continuing series of systems studies in which launch vehicle concepts, designs, and operations are analyzed to determine cost and technology trades and to identify high-yield technology opportunities. The systems studies would be coordinated with related sub-studies conducted in each of the individual disciplines, and with development studies conducted by other agencies and by industry. A considerable portion of the study effort would be conducted by ELV system and subsystem manufacturers.

NASA space programs involve the launching of high-cost, often one-of-a-kind, payloads. The enabling launch vehicle R&T programs have therefore necessarily emphasized performance and mission success. The potential program places stronger emphasis on cost reduction, including technology directed at reducing manufacturing costs. In addition to the R&T activities defined in consultation with the industry, the planned systems studies permit further identification and assessment of cost "drivers" and definition of specific technology efforts and data bases required to support low-cost ELV design and development.

Preliminary prioritization recommendations, particularly in the propulsion area, were obtained during the industry reviews.

In propulsion, the potential program includes analytical and experimental effort to establish a data base on the effects of tolerances on system performance and cost. It includes the generation and verification of technology which could support development of an advanced LOX/hydrogen engine in the 150-thousand-pound thrust class. Such an engine has been identified by portions of the industry as important for improved ELV core stages, and the technology also appears applicable to future large orbital transfer vehicles. Systems studies assessing LOX/hydrocarbon lower-cost evolutionary engine designs would be performed, but augmentation of technology programs for this purpose would be deferred pending determination of industry interest in pursuit of the study results.

The propulsion effort would include provisions for technology effort on low-pressure booster systems, with selection of the liquid/liquid or liquid/solid approach dependent on industry booster studies.

The propulsion activity would build on the NASA Solid Propulsion Integrity Program, providing for an additional effort to develop a more extensive technology data base for design, manufacture, and inspection of composite motor cases. It would also include improved technology for inexpensive (minimum-test) expendable engine qualification.

NASA will facilitate private sector access to key required test facilities for complementary and cooperative technology projects, and for commercial propulsion system development testing.

In materials and structures, the potential program includes the development of advanced aluminum alloy technology and fabrication processes for cryogenic tanks and elevated temperature applications, extending the technology beyond the current aluminum-lithium alloys proposed for use in the ALD program. Similarly, effort would be directed at new composite materials systems for ELV applications, with emphasis on potential for low-cost processing and fabrication. Also included would be research on new materials for tank insulation and advanced thermal protection systems, cost-effective processing and fabrication methods, and improved design, analysis, and test methods for structural integrity and life assurance to ensure high reliability of ELV structures. These efforts would also include testing of subscale and full-scale components to verify the new technologies.

In avionics and operations, the potential program includes development of technology for onboard closed-loop guidance and control to permit greater tolerance to varying wind conditions and hence reduce launch delay costs. It includes the definition and test of advanced fault-tolerant avionics hardware and software to provide real-time fault management and reliability equivalent to that of highly redundant reusable systems but compatible with the low-cost expendable system objectives. It also includes development of technology for an integrated electromechanical actuator, power, and control system with onboard health monitoring capability, directed at eventual replacement of hydraulic systems in future ELVs.

The report also defines efforts on automation for software development, operations, and training, directed at technology advances which could be introduced during ELV block changes as well as in new development.

In the area of aerothermodynamics, no new efforts specifically directed at ELV technology are defined. NASA does, however, recognize the importance of its unique wind-tunnel and computational fluid dynamics (CFD) capabilities in providing the basis for the aerodynamic, aerothermodynamic, and structural load predictions required for launch vehicle design and operation. These essential tools will continue to be maintained and improved for support of government programs, and for assistance as necessary in generating the data bases required for specific new ELV designs. Frequent interchange meetings with industry to make certain that contractors are kept abreast of technology progress in these areas and that NASA remains current as to new development trends and problems. Cooperative programs with industry would be encouraged to increase industry familiarity with these tools and facilitate their use. As in the aeronautics programs, industry requests for NASA R&T effort on specific development problems would be assessed on the basis of the anticipated research value or contribution to the overall knowledge base.

B. PROPULSION

1. Introduction

Industry decisions as to which propulsion systems may ultimately be needed for commercial launch vehicles will undoubtedly require extensive study and will vary depending on the nature of the application. Ongoing NASA and DOD technology and commercial development programs will contribute significantly to the technology advancements and data bases required for future propulsion system development programs. ELV industry access to the output of these technology programs, use of government research and test facilities, and consideration of industry requirements in the government technology programs could contribute materially to the propulsion systems of the future.

Recent discussions with the launch vehicle industry indicate that propulsion technology advances and augmented data bases are needed to support its design and development of a range of candidate lower and upper stage propulsion systems. These systems, listed in order of expressed priority, include LOX/Hydrogen, LOX/Hydrocarbon, Solid, and Low-Pressure Booster propulsion systems for launch stages; and LOX/Hydrogen, Storable Liquid, Solid, and Hybrid propulsion systems for upper stages. Substantial technology data bases currently exist for these engine families, with the exception of the low-pressure booster systems. The potential augmentations to the ongoing technology programs would strengthen research support for the design and development of low-cost expendable launch systems.

The potential propulsion effort is discussed in the following paragraphs, starting with a description of the approach to low-cost engine design and development technology. Then, for each of the engine classes, the applicable ongoing NASA and DOD programs, and the potential effort to focus increased emphasis on low-cost launch systems, are discussed. The additional effort, if undertaken, would complement current programs. In some instances, the required effort does not constitute new activity but rather additional ELV emphasis in research already planned but not yet implemented.

2. Low-Cost Engine Technology

The life-cycle cost elements of any propulsion system, whether expendable or reusable, are the design and development, manufacture, and operation phases. What is sought is the propulsion system that minimizes overall vehicle life-cycle costs, consistent with the performance and operational requirements. An iterative design process that considers and trades the cost of development, manufacture, and operation, in synthesizing the optimum design, can contribute substantially to reducing the life-cycle costs. Technology programs can serve to enhance the life-cycle elements by addressing specific low-cost needs.

An effective approach to low-cost propulsion is to adopt a design philosophy (simpler designs with fewer parts) that accepts less than peak performance, if necessary, to ease the development and manufacturing processes, while making maximum use of standard lower-cost materials and commercial manufacturing processes. The ALD program, which is focused on developing and demonstrating design and manufacturing technologies to achieve low-cost expendable systems, is an example of this approach and should make a major contribution to meeting the propulsion requirements of the ELV industry.

Another approach to lower design and development costs involves the relaxation of tolerances in critical engine components. Tolerance relaxation could lead to significant cost savings as the result of much simpler manufacturing and inspection processes, reduced certification and acceptance testing, and fewer part rejections. Conservative design tradition generally holds that relaxed tolerances lead to compromises in component performance, engine weight, or operating conditions. However, the actual relationship between performance and adherence to strict design and manufacturing tolerances is not fully understood, nor documented. The ELV low-cost engine technology activity would include extensive component-level testing to develop an experimental data base on the real effects of relaxation.

Design and analysis tools being developed in the CSTI program will provide a basis for parametric trade studies permitting identification of the most critical components and a first-order estimate of the impact on performance and weight. The results of these trades would then be factored into the vehicle system studies to establish those engine design approaches that result in minimum overall system costs. The extensive experimental data base, developed at the component and engine system level, would permit verification of the analytical codes and also support subsequent industry low-cost engine design efforts.

The analytical tools to be verified experimentally would include codes to: evaluate the effect of injector element tolerances on combustion performance, stability, and heat transfer; assess the impact of coolant passage tolerances on combustor life; determine the effect of turbine blade configuration and tolerances on flow losses and turbine and pump efficiencies; determine the impact of reduced tolerances in bearings and seals; and assess the effects of tolerances on the structural response and predicted life of the engine components being studied. The experimental data and the verified analyses could establish the feasibility of cost reduction through tolerance relaxation.

3. Liquid Oxygen/Hydrogen Propulsion

As expressed in the industry advisory group rankings, high-performance LOX/hydrogen propulsion is the highest-priority need for future system developments. It can be used for all launch vehicle stages, and has also been proposed for a combined second and upper stage configuration. The ALD program addresses low-cost manufacturing processes, design concepts, and development and testing of full-scale critical components including turbopumps, thrust chambers, and gas generators, for large (400,000- to 600,000-pound thrust capability) engines for ALD concepts. Some but not all of the information resulting from this effort will be generally applicable to LOX/hydrogen engines regardless of the intended thrust level.

In some segments of the ELV industry there is a strong interest in a smaller (approximately 150,000-pound thrust class) engine operating on a high-performance engine cycle for combined second-stage and upper-stage applications. Other segments of the ELV industry prefer a near-term alternative to the new-engine approach, favoring for upper-stage applications an upgraded version of the RL10 engine with somewhat higher thrust and performance. The thrust level would be too low for cost-effective application to a new booster or second stage propulsion system, but the upgrade could provide appreciable Centaur improvement.

The interest in the new medium-thrust engine creates a need for associated technology and an engineering data base which could support development of such an engine including, where required, throttleability, high-altitude ignition capability, and variable mixture ratio. Much of the basic technology for high-performance engines is currently being addressed in NASA's CSTI Earth-to-Orbit (ETO) and Exploration Technology Chemical Transfer Propulsion (CTP) technology programs. These programs are designed to provide new concepts and improved tools for the design and development of minimum-cost launch vehicle, upper stage, and space-based engines. The Exploration Technology CTP program will also produce an integrated breadboard engine in the 5,000-50,000 pound thrust class.

Because of the strong industry view as to the importance of the 150,000-pound-thrust class propulsion system, and because it could involve very costly development, the technology effort would be similar to that being conducted in the ALD program for the larger thrust engines. It would be directed at establishment of a validated technology base, developed for low-cost systems and components in an experimental engine system design, fabrication, and ground-test program. Expander, split-expander, or gas generator cycle options would be considered, possibly with the added capability to operate over a range of mixture ratios (from conventional hydrogen-rich to oxygen-rich) for selected applications.

Cycle trades permitting selection of one of the three cycles on the basis of performance and cost would be included. Thorough investigation of this system, including a point design with accompanying performance and cooling analyses over the mixture ratio and throttling range, may give rise to additional technology needs not now evident. The approach would be to analyze the system, develop any technologies fundamental to the system that are not being addressed in current programs, such as oxygen-rich combustion and materials compatibility in a high-temperature oxygen-rich environment. The final step would be to perform a detailed system design, fabricate and test components, assemble a breadboard system, and conduct system-level tests to obtain performance and cost data.

4. Liquid Oxygen/Hydrocarbon Propulsion

Advanced pump-fed LOX/hydrocarbon engine technology for future large ELVs is included in the ALD program. In addition, evolutionary improvement of LOX/hydrocarbon propulsion is an option for reducing the cost of existing expendable launch vehicles. The LOX/kerosene combination was used in the Saturn vehicles, and is currently used in the Atlas and Delta vehicles. The adaptation of improved LOX/hydrocarbon propulsion systems to Atlas and Delta (to replace both solid and liquid systems), as well as to the Titan family (which currently utilizes solid booster strap-ons and storable propellants for their liquid stages) could lead to reduced operating costs and reduced environmental problems for these already operational systems. General technology support for pump-fed LOX/hydrocarbon propulsion systems is being addressed in NASA's CSTI ETO program. However, specific focus on low-cost evolutionary LOX/hydrocarbon technology for existing ELVs would require redirection and augmentation of the current program to support low-cost design approaches at the engine system level. The vehicle system studies would identify technology needs for this evolutionary approach and can be used as a guide to defining appropriate technology program augmentation if industry proposals indicate a need for such effort. Additional LOX/hydrocarbon activity may also materialize in the area of low-pressure booster propulsion discussed below in paragraph 6.

5. Solid Propulsion Systems

Cost and reliability of current solid propulsion systems represent significant industry concerns relative to both lower and upper stages. Much of the needed technology is presently either being worked in various DOD programs and the NASA Solid Propulsion Integrity Program (SPIP), or has been planned for future efforts in support of U.S. government requirements. The DOD programs are currently focusing on insensitive, high performance, and low signature propellants. The solid propulsion portion of the ALD program is focusing on clean burning, low-cost propellant processing, the development of a non-asbestos insulation, and composite motor cases.

The SPIP, a national program developed in cooperation with DOD and industry, is designed to put in place the engineering capability for improving the success rate of U.S.-built solid rocket motors (SRM). It is directed principally at improving the science and engineering for materials data bases, design capability, manufacturing, and product verification, and at advancing the community infrastructure and culture. The program is designed to address seven key solid propulsion issues: composite motor cases; propellant and insulation; nozzles; bondlines; combustion dynamics/internal ballistics; joints and seals; and verification testing. Propellant, nozzle, bondline, combustion dynamics, and verification efforts are now under way. The industry indicated that, with added emphasis on composite motor cases for ELV applications, the originally planned SPIP, together with the ongoing DOD programs, would in general satisfy their solid propulsion needs. At present, NASA SPIP planning does not include the composite motor case task, and this area is being worked only to a limited extent in the ALD and other military programs. To effectively address this significant ELV need, the potential program would contain added composite motor case technology effort as described in Section C, Materials and Structures.

Coverage of the technologies for clean burning, low-cost propellant processing, and the development of non-asbestos insulation in the ongoing programs appears adequate. The problem of emergency thrust termination for solid propulsion systems is an area of concern to some of the industry. The effort would include further study of alternative solid rocket thrust termination concepts, leading to possible subsequent technology effort if promising new ideas for solution are defined.

6. Low-Pressure Booster Propulsion

A number of low-pressure propulsion system alternatives, both near-term and far-term, show promise of significantly reducing ELV operating costs when compared to the higher-pressure pump-fed liquid systems and solid rocket motors in use today. Near-term options include both liquid/liquid systems and liquid/solid hybrid systems that offer greater simplicity, thrust tailoring, thrust termination, and potentially higher performance. The liquid propellants in these systems can either be pressure-fed from pressurized tanks or pump-fed with very simple, low-pressure-rise pumps. Simpler engine component designs can reduce propulsion system costs -- e.g., one-piece metallic combustion chambers with ablative liners, composite nozzles, and much simpler injector designs. Low-weight tank pressurization concepts for the pressure-fed systems are a key technology issue, since the tanks represent a significant percentage of overall system mass.

The technology base for these systems is not as fully developed as for the systems currently in operation, although a small hybrid motor development is being pursued in a proprietary commercial venture by the American Rocket Company (AMROC). Technology issues associated with both liquid/liquid and hybrid systems are being addressed in NASA's propulsion technology programs. The liquid/liquid focus is on pressure-fed applications, and the hybrid focus is on eventual application to very large (2.5 million pounds thrust range) boosters. Industry interest in using these systems in commercial launch vehicles could provide the initiative to augment ongoing programs to address technology issues unique to the ELV application. The effort would begin with system studies and selection of a system/concept approach and would progress, through analysis and code development, to subscale code evaluation and full-scale technology verification.

More innovative options, with much greater potential future payoffs, include the use of metalized gelled propellants or solid oxidizers. These approaches again offer simplicity, thrust tailoring, and thrust termination, but their higher energy density also offers compactness (increased performance in a much smaller package) that could result in significant additional cost savings. NASA and Air Force are evaluating the feasibility and true potential of these approaches in long-term research programs at low funding levels. The vehicle system studies would assess the benefits of these innovative approaches, determine the most promising concepts, and identify critical technology issues that need to be addressed for the selected concepts. If the studies generate industry interest in such systems, an appropriate technology program for the selected concepts could then be defined.

7. Upper Stage Propulsion

Currently operational upper stages and their respective propulsion systems include Centaur (pump-fed LOX/Hydrogen), Transtage (pressure-fed storables), Payload Assist Module (PAM) (solids), and Inertial Upper Stage (IUS) (solids).

Storable propellants and solids offer only moderate performance, but provide compactness and excellent in-space storability. LOX/Hydrogen propellants offer high performance, but because of liquid hydrogen, are large in size and are difficult to store in space for lengthy periods of time.

Advanced upper stage propulsion systems, both near-term and far-term, have the potential of providing higher performance at lower cost for expendable launch vehicle applications. For example, a technology effort has been under way for a number of years and is now being brought to maturity by the development under Air Force sponsorship of a 3,750-pound-thrust storable high-pressure pump-fed engine called the XLR-132. This program is planned for continuation through prototype demonstration and perhaps development. Industry is counting on continuation and completion of this ongoing effort, and additional support does not appear to be needed at this time.

An alternative storable-propellant engine could be a low-pressure pump-fed version of the pressure-fed Shuttle Orbital Maneuvering Engine (OME). Small conventional liquid/solid hybrids are also candidates for upper stage propulsion systems, offering somewhat higher performance than currently operational systems while maintaining compactness and in-space storability. The hybrid technology efforts under way in the Low-Pressure Booster Propulsion program would be applicable to the small hybrid upper stage systems. Similarly, the more advanced metalized gelled propellants and solid oxidizers discussed above may provide significant performance enhancement for upper stage applications and can be assessed in the systems studies to determine the need for additional technology focus in this area.

8. Facilities

Nationally there are a limited number of operational propulsion test facilities in government and industry. To support the ALS program and NASA's focused propulsion technology efforts in the CSTI and Exploration Technology programs it has been necessary to build a number of new facilities and to expand the capability of existing NASA and DOD facilities. Even with the new capability, some additional facilities would be required to support the propulsion portion of the potential ELV program. New test facilities for the additional technology development and verification would include component test facilities for liquid oxygen, hydrogen, and hydrocarbon turbopumps and thrust chambers, and for testing complete liquid, hybrid, and solid propulsion systems. The systems test facilities could be provided by modifying NASA facilities already in place at the Stennis, Marshall, or Lewis Centers. Some component tests may require new facilities. Provisions could be made for use of the new or modified research facilities in cooperative NASA/industry technology programs, as is done in existing test facilities.

C. MATERIALS AND STRUCTURES

1. Introduction

Industry representatives involved in ELV design, development, and production have identified a number of materials and structures technology needs. Technology needs for the U.S. government will be met by current programs such as ALD, SPIP, NASP, and the NASA and Air Force research and technology base programs. However, the industry engineers cited a number of key technology areas that may need greater emphasis. This section of the report identifies essential materials and structures technology effort that industry believes is required in addition to the current programs to provide the technology and foster the development of cost-effective ELV systems for future government and commercial launch operations.

High-priority technology needs identified for near-term applications include: expanded efforts in advanced materials and structures for low-cost cryotanks including aluminum-lithium metallic tanks and filament-wound composite structures; low-cost composite dry structures; advanced thermal protection systems; and low-cost manufacturing and processing methods. In addition, improved design/verification methodology is required for structural integrity, including launch loads and payload dynamics, to insure high reliability of future ELV structures. Longer-term needs include development of new materials, such as advanced aluminum-lithium alloys and thermoplastic composites for cryotanks, interstage and shrouds.

The following paragraphs discuss the ongoing efforts and the appropriate augmentations for each of the major materials and structures technology need areas. The effort required to develop an extensive technology base to support industry design, development, and fabrication of low-cost ELV systems for use in government and commercial operations includes: evaluation of structural concepts and trade studies; materials development; design, fabrication, and test of structural elements and subcomponents; and intermediate scale-up leading to large-scale validation.

2. Structural Concepts Definition/Trade Studies

The technology efforts would begin with studies performed to identify and evaluate opportunities for ELV reduced cost and improved performance based on materials and structures technology advances and innovative concepts. Trade studies evaluate materials benefits, advanced processing and fabrication methods, innovative structural concepts, structural performance, and manufacturing costs to identify high-payoff materials and structures technologies for ELV applications. Results of these studies provide a guide for establishing technology focus and emphasis, and for identifying additional technology opportunities for follow-on activity.

3. Aluminum-Lithium Cryotanks

Current ALS program efforts are focused on development, fabrication, and testing of cryotanks using existing aluminum-lithium alloy systems (ALCOA 2090, ALCAN 8090, or Reynolds Weldalite™ 049). These efforts vary in scope, but all focus on demonstrating critical cryotank technology objectives, including weldability, LOX compatibility, low-temperature performance, and fabrication of aluminum-lithium structures. The ongoing programs will provide an initial assessment of aluminum-lithium cryotank structures and a limited materials data base on current aluminum-lithium alloys, but are not directed at development of new materials with improved properties. To provide a data base on materials performance, forming, fabrication and welding, inspection, and durability sufficiently broad for scaleup to full-sized structures, additional effort may be required.

The additional effort would include the development of new aluminum-lithium materials for cryotank structures with improved weldability, formability, short transverse fracture toughness, LOX compatibility, and reduced anisotropy. The research would also expand on current ALD effort to focus on new aluminum-lithium alloys with improved superplastic forming capabilities for fabrication of complex structures such as isogrid reinforcement of cryotanks. It would include development of new high-temperature aluminum alloys with improved thermal resistance for high-temperature applications. These new alloy developments should lead to advanced designs with reduced structural weight and fabrication costs. Raw materials cost may also be lowered as a result of developing alternatives to Weldalite™, which is currently the only available material that is LOX-compatible.

Weldalite™ -- a Martin Marietta trade mark

4. Composite Structures

Extensive developments in composite materials and structures have led to major applications in aeronautical vehicles. Past composites technology efforts have resulted in the development of filament-wound solid rocket motor cases for strategic missiles. NASA has recently initiated a major program in advanced composites technology for aircraft structures, which is focused on developing new materials, innovative designs, advanced design methods, low-cost fabrication, and structural test and verification of critical subcomponents. These programs will extend the existing composites design, fabrication, and production data base, and will result in major advances in composites technology. The ALD program addresses low-cost composites for ELV dry structures, including a filament-wound subscale intertank and composite shroud subcomponents using low-cost commercially available materials.

The potential additional effort includes the identification and development of new composite materials systems, derived from the NASA research, with the potential for low-cost processing and fabrication. One example is the ongoing NASA research in new materials for resin transfer molding. Application of these materials and fabrication methods to a broader range of ELV structures offers the potential for further cost reductions. For example, composite cryotank technology development is not considered sufficiently mature for the ALD program. The potential program provides for the development and full-scale structural testing of a composite cryotank, and for establishment of an adequate data base to facilitate industry application of the new composite materials. It would also include composite solid rocket motor case technology effort, with emphasis on smaller sizes and production cost issues.

5. Thermal Protection Systems

Low cost thermal protection systems (TPS) with improved environmental acceptability are being developed as part of the ALD program. One of the new TPS materials under development is a spray-on foam insulation (SOFI) with an improved blowing agent to replace the current chlorofluorocarbon material. This TPS material could provide an adequate measure of thermal protection for external tanks in existing ELV systems. Another material development is a replacement for the existing Shuttle tiles with improved toughness and durability. To optimize cost, weight, and performance, future ELV structures may require integral thermal protection systems. Advanced materials for integral TPS can provide improved performance, but will require further development and optimization.

The program would include development of new TPS for integral tank structures with internal as well as external insulation. These TPS concepts build on past research in evacuated metallic insulation, foam insulation, and hybrid systems. The additional TPS efforts would supplement the current ALD focus on SOFI materials to provide a capability for optimum design of ELV thermal protection systems.

6. Advanced Processing/Fabrication Methods

Current programs in processing and manufacturing technology for composite and metallic structures have generally focused on developing new technology for low-cost fabrication. For metallic structures these programs have focused on superplastic forming, spin forming, automated welding, and in-process quality control, and have demonstrated the benefits of these technologies on panels and subcomponents using current materials systems. Composite structures programs are exploring a broader range of fabrication options with the potential for reduced cost, including filament winding, automated tape layup, pultrusion, cocuring, and thermal forming. The ALD program will demonstrate some of these techniques on selected components, such as automated assembly and welding of a 2219 aluminum cryotank dome, fabrication of small-scale aluminum lithium tanks, and filament winding of a composite intertank structure. However, additional effort is required to obtain the full benefits of these new cost-effective processing and fabrication methods for ELV applications.

The potential new effort includes development of focused advanced processing and fabrication technology for advanced aluminum-lithium cryotanks and composite cryotanks with integral metallic and non-metallic liners, fabrication of composite structures for payload shrouds with integral damping concepts, fabrication of integral TPS systems, and improved processes for automated welding, inspection, and assembly of cryotanks. Other ELV processing and fabrication requirements identified in the structural concepts definition studies can be addressed in subsequent effort.

7. Integrated Data Base/Design Methods

To facilitate the application of technology to new ELV developments, the program would include establishment of an integrated design data base for materials and structures, including: design concept evaluation; design methods; materials characterization; element and subcomponent test data; details of processing, joining, environmental testing, and nondestructive evaluation (NDE); and results of materials and structures developments in the ALD and other ongoing research programs.

The design methods and design verification tasks would include development of methodology for assessment of structural integrity and life predictions of ELV structures and payloads to insure high reliability. The effort would also include the testing of dynamic scale models to verify launch and separation design loads prediction methods. New design methods such as structural tailoring for composite structures, developed in the NASA Advanced Composites Program, would be extended to ELV structures for design of innovative concepts for low-cost structures.

8. Scale-Up Structural Test and Verification

The potential program includes verification of the newly developed materials and structural concepts through tests of subscale and full scale subcomponents. This level of verification is similar to the efforts planned for ALD and would provide the data base necessary for a full scale proof-of-concept test article. Critical components with promising potential for application in commercial ELV systems, including elements demonstrated in the ALD program, may be selected for ground testing and possibly subsequent flight testing. The potential filament-wound solid rocket motor case effort is an example of a component that would be subjected to structural test and verification.

9. Facilities

Implementation of the Materials and Structures effort may require some new facilities or upgrades such as: capabilities for filament winding and automated tape layup of composite cryotanks, and advanced interstage and payload shroud designs; thermal structures testing facilities for composite and metallic cryotanks to verify new materials and TPS concepts; and laboratory capabilities to develop advanced aluminum-lithium and high-temperature aluminum materials for launch vehicle applications. The existing and new facilities would be suitable for use in cooperative NASA/industry research.

D. AVIONICS AND OPERATIONS

1. Introduction

NASA's R&T Base and the ALD program contain efforts directed at autonomous, adaptable, and fault-tolerant avionics systems to increase reliability, safety, and flexibility, and to reduce cost. The ongoing programs also include technology for reduction of operations manpower, time, and cost. However, opportunity exists for additional avionics and operations technology that can benefit both government and commercial ELVs. Moroover, the industry inputs indicate that flight validation to reduce the risk of new technology application is a particularly important consideration for ELV avionics.

The potential effort discussed in this section, covering both expendable earth-to-orbit and orbital-transfer vehicles, would complement the ongoing programs by providing additional avionics and operations technology specifically directed at ELVs and suitable for practical utilization. It would include near-term application of existing technology as well as high-payoff new technology for the future.

The effort would involve considerable systems study and economic modeling effort, in conjunction with the ELV industry, to identify and evaluate cost drivers and the effects of potential near-term and future technology advances.

2. Guidance and Control for Upper Winds Loading Relief

Advanced guidance and control could permit real-time adjustment to wind dispersions, potentially eliminating much of the pre-launch manual flight planning and trajectory design procedures which increase launch operations uncertainty, cost, and time. The ALD program includes an effort directed at technology that will enable a next-generation launch vehicle to carry out a sophisticated form of guidance based on onboard LIDAR measurement of atmospheric conditions ahead of the vehicle. Ongoing NASA programs are developing air data sensor technology and wind profile measurement systems which will provide an essential capability for a variety of guidance and control systems for advanced manned launch systems.

The additional effort would be directed at a control system which utilizes the NASA-developed ground-based wind profile measurement system upgraded as necessary, a communications link with the ELV, and ALD or new onboard algorithms to keep the vehicle within prescribed load limits. Such an approach would be suitable for incorporation in incremental and block changes on existing ELV systems.

Early flight testing would be conducted on a small launch vehicle or sounding rocket, or as a self-contained payload on an existing ELV or Shuttle. Following the definition of ELV guidance and control requirements, the onboard algorithms and system performance necessary to satisfy the launch vehicle attitude and trajectory constraints would be established. The necessary software and hardware would then be defined and developed, including onboard computers and ground support elements. Integrated testing would be performed to ensure that the system meets all requirements as a test article for use in the validation flight test program.

3. Next-Generation Fault-Tolerant Avionics

Considerable effort in government and industry programs is being devoted to the development of technology for fault-tolerant avionics systems. Technology being addressed in the ALD program and in some of the NASA research is directly relevant to ELVs. Commercial ELV economic factors, however, may suggest different reliability criteria and thus different solutions for commercial ELVs than those dictated by unmanned military mission success or human safety considerations for manned flight.

To assess the impact of fault-tolerant avionics technology on expendable vehicle ground and flight operations, and to determine the fault-tolerant avionics features most important and appropriate to ELV systems from a standpoint of total system cost, performance, and reliability, the program would include cost model development and cost-benefit analyses. The analytical process would include the synthesis of a representative ELV avionics workload for use in assessing performance and reliability of candidate fault-tolerant architectures. It also includes definition and evaluation of a conceptual optimized fault-tolerant avionics system for application specifically to ELVs to identify associated technology requirements.

A closely related technology of potential importance to the ELV industry is that of formal verification (i.e., design proof) for avionics systems. Formal verification is a process of mathematically proving that each step of the design process is consistent with previous steps and with the original specification. Its objective is to eliminate design flaws and common mode failures early in the design process, where change is the least expensive. It involves the use of formal specification languages, mathematical logic, semi-automatic theorem provers, and other tools not yet fully developed. Formal verification is not sufficiently mature for application to an entire avionics system. To further the development of the technology for ELV application, the effort would include selection of at least one critical subsystem from the candidate fault-tolerant avionics system definition to be subjected to formal verification. This would involve the formulation of formal specifications and proof of successive hardware and software design steps -- where possible, empirically verifying proof assumptions and constraints in controlled experiments.

4. Photonics Technology for Far-Term Flight-Crucial Systems

Optical technology can be applied to aerospace system architectures and components and offers the advantages of inherent parallelism leading to high data rates, lower power, weight, and size requirements for a given computational or technological capability, resistance to electromagnetic and high-energy radio-frequency interference, and a higher degree of fault tolerance. Photonic systems have fewer discrete active components and physical connections than electronic systems, and optical architectures are generally more resistant to single-component failures. Photonic technology could eventually be used throughout the launch vehicle for data acquisition, high-speed communications, and rapid information extraction and analysis. Finally, digital and analog optical systems can be used for high-speed onboard computing, including data analysis.

Currently, component technology is being pursued in OAET R&T Base programs, with the Fiber Optics Rotation Sensor being representative of the most advanced technology. The ALD program is pursuing a laser-initiated pyrotechnic device to reduce both the hazard and the ground processing cost associated with ELV active ordnance devices. Exploration Technology program plans include a photonics initiative involving optical processor architectures and algorithms, spatial light modulator development, and fiber optic networks. Focused photonics efforts are also planned under aeronautics R&T programs.

Photonics technology specifically directed at ELVs is not contemplated. However, ongoing aeronautics, space, and exploration technology efforts would be monitored so that results can be utilized in the ELV systems studies where appropriate, and focused ELV photonics effort can be implemented when progress warrants separate emphasis.

5. Integrated Electromechanical Actuators, Power, and Controls

Progress is being made in a number of government and industry programs on integrated electromechanical actuators (EMAs), power, and control systems -- a technology of considerable potential benefit to ELVs. The resultant elimination of hydraulics, auxiliary power units, and ground support carts and equipment offers promise of major improvements in launch vehicle economy, dispatch reliability, safety, and servicing, test, and operational efficiencies. These benefits have been quantified in several aircraft and space systems studies, including studies showing pre-launch testing savings of thousands of manhours for Atlas/Centaur launch vehicles and even greater savings for the Space Shuttle.

The promise of improved performance using EMAs is currently being demonstrated in cruise missiles, and EMAs have been tested successfully in several flight and laboratory experiments. The ALD program includes ground demonstration of large (25 to 50 hp) actuators. The focus of the potential program effort is on adapting the EMA technology to machines in the 1 to 5 hp and 5 to 20 hp sizes and conducting flight tests on current-generation ELVs.

The effort would begin with development of performance and operational requirements for integrated EMAs, high-frequency electrical power systems, intelligent control, and built-in test equipment (BITE). It would then proceed to fabrication, integration, and flight test of an experimental actuator/motor/controller combination including the remote checkout provisions.

6. Automated Ground and Launch Operations

The application of automation to ELV systems has the potential for reducing manpower needs, improving safety and performance, increasing reliability, and reducing turnaround times and costs. Advanced flight vehicles rely heavily on software to accomplish their missions. The cost of designing, developing, testing, and maintaining avionics software is becoming an increasingly large part of total life-cycle cost. Discussions with industry indicated that new software engineering technologies will be introduced incrementally. For example, it would probably not be feasible to use new methods to reengineer software in existing ELVs. However, many aspects of testing and validation could be automated. Advances such as automation of communication between ELV data bases could reduce operational costs and turnaround time, eliminate reentry of duplicate data, eliminate the need to track duplicate data across multiple data bases for maintenance purposes, and facilitate transfer of data between data bases.

The ALD and the CSTI programs and the Office of Space Flight's advanced development programs contain activity directed at the application of state-of-the-art expert systems and robotics technology to advanced operations. Among its cost-reduction activities, the ALD program includes an effort to improve the software development environment. It is tailored to new system development and ALS architecture specifics, and may not be applicable to existing ELV families or to the variety of new ELV developments, advanced computer architectures, and parallel processors to be anticipated in the future.

The CSTI Automation and Robotics (A&R) program includes activities to demonstrate the use of expert systems for real-time fault detection in Shuttle flight operations and the application of artificial intelligence (AI) and robotics to streamline ground operations. Additionally, the A&R program is developing new generic technologies having broad aerospace applications, including efforts related to learning, planning and scheduling, intelligent assistants, intelligent agents, and large knowledge-based systems.

The additional effort on this subject would be intended to facilitate the transition of ALD and CSTI automation technology to the ELV industry. It would include automation technology for software development, operations, and training, as applied both to specific near-term and generic future expendable vehicles. The objective would be to develop technology advances which could be implemented at various stages in the progress of the vehicle programs -- some requiring no significant modification, some appropriate for incorporation during major block changes, and some feasible only in new development.

The effort would start with a series of studies to develop system models as a basis for definition of technology needs for automation of future systems. For several existing ELVs, studies would examine launch operations requirements, software needs, and cost drivers, to define the system architecture and technology requirements for an integrated automated system capable of supporting development, maintenance, and operation of all of the software and hardware associated with preflight, flight, and ground support. The studies would include the identification of areas in which operations might be simplified, for commercial operations, by elimination of requirements solely related to unique government mission or operational considerations. Although the studies might identify opportunities for application of some automation benefits to existing ELV families in the near term, the primary purpose would be analysis and integration of the individual system definitions to support definition of a generic ELV system for use in identifying new technology needs for future automated systems.

The software technology portion of the effort would apply specifically to ELVs the benefits of two promising new software engineering approaches currently under evaluation for ALS application -- Computer-Aided Software Engineering (CASE), and software reusability. It would include the development of requirements, concepts, methodologies, and tools for an integrated software environment workstation for use by the industry to support the automation of software development and maintenance processes and software reuse in ELV development.

NASA has been developing Intelligent Computer-Aided Training (ICAT) systems, and planning and scheduling systems based on expert systems technology, for use in Shuttle and other government programs to achieve improvements in economy, reliability, and safety by automating the operations personnel training process and the planning and scheduling processes.. The program would include efforts to facilitate the application of these technologies -- e.g., knowledge-based interactive training systems -- to ELV operations.

7. Test Capabilities

NASA program offices, in conjunction with the ALD program, are currently considering two new capabilities which could be of considerable value to the ELV industry.

An avionics productivity center is being considered as a mechanism to facilitate the transition of new avionics technology into launch vehicle development. At present, schedule and cost risks involved in space-qualifying new technology can in some instances deter the application of available technology. The purpose of the center would be to permit verification of hardware and software technology in a simulated flight environment prior to actual vehicle use. If such a productivity center is appropriate, the U.S. government would work with industry to provide practical protected use by industry, either in cooperative government/industry component and subsystem technology programs or in proprietary commercial development efforts on a reimbursable basis. These provisions could include, for example, the definition of ELV-industry-unique requirements, the development of industry ELV simulation software, and the addition of company-secure hot bench experiment processing facilities and work stations to enable ELV industry test and evaluation of new software and hardware in a systems environment.

The other potentially valuable new capability being considered is an automated operations and management testbed, a laboratory intended to permit experimentation, validation, and evaluation of automated operations hardware and software in high-fidelity launch support simulation. The primary purpose of the testbed would be to provide an off-line but realistic laboratory environment in which automation and robotics researchers can work together with engineers and technicians experienced in real-world operational support activity. The culture of ground operations has evolved over a long period of time and has proven largely successful, albeit manpower-intensive and time-consuming. If the automation and robotics technology being generated in the universities and research laboratories is eventually to be incorporated in actual practice, it must be guided not only by the academic and research community but also by the experienced hands-on operators as well. Here also, if the testbed is developed for use in government and university research and technology programs, additional features could be provided for convenient and, if necessary, proprietary utilization by industry.

E. RESOURCES

The potential program reported herein is intended to supplement relevant R&T Base, CSTI, Exploration Technology, and ALD programs -- the primary ongoing technology efforts to improve U.S. government and commercial launch capabilities. The President's FY 1991 NASA budget requests about $55 million for technology and $40 million for ALD propulsion development efforts. The funding requirements for implementation of the potential program would depend on the status of those ongoing programs and the extent of cost-sharing approaches with industry based on industry's commitment to such a program. In some areas, funding requirements would be determined on the basis of program details defined following system studies conducted to identify the major technology cost drivers. The additional efforts identified in the report have not been funded, based upon ongoing assessments of relative priority vis-a-vis the existing programs.

APPENDIX A

NEAR-TERM ASSISTANCE TO INDUSTRY

The long-term viability of the nation's commercial ELV industry may be decided in the marketplace in the near term (3 to 5 years), rather than by long-term strategies. Recognizing this, NASA asked the ELV and satellite industry, through the Department of Transportation's (DOT) Commercial Space Transportation Advisory Committee (COMSTAC), to respond to the following question:

> "What can NASA do to aid the domestic commercial launch vehicle and satellite industry in the increasingly competitive international marketplace from 1990 and beyond?"

The objective was to identify what NASA might do in the near term to aid the commercial ELV and satellite industry both by technology developments and policy/administrative actions that could lower cost or increase reliability. Emphasis is placed on cost and reliability since, although they are not the only factors considered in the selection of a launch service or a satellite, they are dominant factors.

The COMSTAC response suggested near-term technology developments that could result in early adoption by the commercial ELV industry. However, COMSTAC noted that technology development, indeed, development of new commercial launch vehicles, by their foreign competitors are government funded.

COMSTAC reports that ESA is developing a brand new ELV, Ariane V, along with the associated launch complex infrastructure. The planned investment is $4 to 5 billion with an objective of reducing launch costs 40 percent. China and Japan have launch vehicle development programs under way. However, the domestic commercial ELV industry must capitalize the adoption of new technologies and amortize these costs within their launch service price. According to COMSTAC, ESA and China fund their ELV development cost, while their commercial marketing entities bear only the incremental launch services costs.

Table A-1 summarizes COMSTAC's suggestions of near-term policy and administrative actions that the government should continue or initiate to maintain or improve the industry's competitive posture in international markets. Many of these suggested policies and administrative actions are currently in place while others need renewed emphasis or clarification.

In response to policy directives, NASA, like the Air Force, has developed use agreements that provide private sector ELV operators access to NASA property and services. NASA has instituted a two-tier commercial use agreements process. Headquarters agreements specify the general terms and conditions under which ELV operators may use NASA ELV property and services. In addition, the Headquarters enabling agreements authorize industry to negotiate sub-agreements with the appropriate NASA field centers for use of specific NASA property and services. Table A-2 lists the status of both Headquarters agreements and field center sub-agreements.

NASA property/services will be provided to the commercial ELV community on a non-interference, cost-reimbursable basis. NASA services will only be provided to the commercial industry, if the requisite services are not available from the private sector.

Four NASA Headquarters Commercial Use Agreements have been signed to date with General Dynamics, McDonnell Douglas, Martin Marietta, and LTV Aerospace. Four additional Agreements are currently in negotiation with Orbital Sciences Corporation, American Rocket Company, E'Prime Aerospace, and TRW.

Kennedy Space Center has three signed Sub-agreements with McDonnell Douglas, Martin Marietta, and General Dynamics. The Kennedy/General Dynamics sub-agreement was an important milestone, since it was the first NASA Commercial Use sub-agreement and since it allowed General Dynamics to take over the operations and maintenance responsibility for the Atlas/Centaur launch complex at Cape Canaveral Air Force Station. Goddard Space Flight Center has signed a sub-agreement with McDonnell Douglas to provide technical transition support of their first four commercial Delta launches. Marshall Space Flight Center has signed a sub-agreement with Martin Marietta to support acoustic testing of the commercial Titan III. The Office of Space Operations has signed a sub-agreement with McDonnell Douglas to provide support of NASA's ground based tracking and data stations to the commercial Delta program. Approximately seven additional Subagreements are in various stages of negotiation with industry. In addition, NASA has consummated Commercial Use Agreements with both Space Services, Inc. and Conatec for support to commercial sub-orbital operations at Goddard Space Flight Center's Wallops Flight Facility.

In addition to COMSTAC's ideas noted above, the Office of Space Flight (OSF) has identified several actions that could also assist the ELV commercial community. These are:

• Establish an ad hoc task team with members of COMSTAC with the charter to assess the near-term policy and administrative suggestions offered by COMSTAC (Table A-1) and OSF. A consolidated action plan agreed to by both the ad hoc industry team and NASA would be approved by the NASA Associate Administrator of Space Flight. This action plan would define the steps necessary to bring to resolution or closure each suggestion or initiative. In some cases, Congressional consultation or action may be required.

• OSF to serve as an advocate within NASA for the operational commercial ELV community. OSF will work to ensure the ELV community is kept apprised of NASA activities and developments in a timely manner. Specifically:

- Continue to encourage the use of NASA's operational test facilities/services to the commercial ELV industry. The NASA Office of Commercial Programs publication entitled, Accessing Space, describes some of these in greater detail.

- Provide to industry, upon request, technical teams of ELV discipline experts to critique new vehicle designs, new operational procedures, etc. For example, Orbital Sciences Corporation invited NASA to attend and participate in the critical design review of the Pegasus launch vehicle. Also provide technical teams to participate in the initial Flight Readiness Reviews of new launch vehicles and vehicle configurations.

- Assist industry in the acquisition of launch sites and design of launch and payload processing facilities that would allow industry to be independent to the maximum extent feasible of U.S. Government programs where there are threats of U.S. Government preemptive disruptions of commercial operations.

- Where feasible, facilitate the flight test of promising new ELV technology applications on U.S. Government missions without jeopardizing mission success.

• Initiate a program of small, low cost space payloads. These payloads could be proof of science or technology applications concepts attendant with the acquisition of promising new small class ELV launch services.

The launch services, like the payloads, would serve to test and demonstrate new ELV technologies, where such technologies do not overly compromise mission success. NASA could provide flight opportunities for small low cost/high risk scientific, application or technology payloads, and could procure commercial launch services for these satellites on a competitive basis. The launch service selection criteria could emphasize low cost, innovativeness, and flexibility, rather than a probability of mission success exceeding the 96 percent norm expected for NASA's small and medium performance class launch services. Offerors on NASA's flight opportunity launch services could be encouraged to propose and demonstrate new technology components that promise lower cost or higher reliability. NASA may from time-to-time piggyback new technologies on its missions. These proof-of-concept demonstrations of new technologies could certify designs before commitment to in-line performance or mission success.

POLICY

- NASA sponsor U.S. commercial ELV technology developments.
  - establish equivalent of NACA Aeronautics Model Program
  - focus on cost reduction and reliability enhancements
  - oversee integration of new technologies into vehicle
- Procure U.S. Government civil launch services from domestic commercial ELV operators, whenever possible.
- Provide long-term contractual commitments for launch services.
- Provide support to the nonrecurring development tasks associated with implementing new component technologies into vehicle.
- Eliminate U.S. Government's preemptive rights in shared facilities.
- NASA develop a new efficient, low cost, reliable ELV in the 6000 to 10000 pound performance range to Geotransfer orbit.

ADMINISTRATIVE

- Prior to solicitation for research, development or technology projects, undertake a review of existing private activities in that area to assure it does not duplicate privately funded work.
- NASA conduct cooperative flight test programs of new technology applications.
- Provide on-going access to NASA's libraries, research facilities, and real-time access to test data.
- Improve access to technologies owned by the U.S. Government, particulary DoD.
- Add emphasis on joint endeavors and perhaps direct subsidies to attract technologies that may become markets of the future.
- Consider restructuring NASA to split R&D from operations.
- NASA become permanent interface with the Air Force at the launch ranges for all civilian launch vehicles and satellites.
- Rigorously enforce trade agreements with foreign ELV competitors.
- Formally institutionalize commercial ELV procurement practices.
  - eliminate cost and pricing data certification
  - allow commercial payment schedules
  - delete Federal Acquisition Regulation requirements not appropriate in commercial procurements.
  - relax data and oversight requirements consistent with a commercial program.

Table A-1. Summary of COMSTAC's Suggested Near-Term ELV Policy and Administrative Actions

COMPANY	HEADQUARTERS - UMBRELLA		CENTER - SUBAGREEMENT		
	STATUS	CONTENT	CENTER	STATUS	CONTENT
GENERAL DYNAMICS (Atlas I/II)	March 1987	Use of Prod Tooling, STE, GSE/ Launch Service Support	KSC	March 30, 1988	• GD - O&M of Complex 36 • Use of Launch Support Services
	Modification 1 November 1988	Incl Use of Facilities	LeRC	Draft in Review	• Use Of Technical Support
McDONNELL DOUGLAS (Delta II)	September 1988	Use of Launch Support Services	KSC	December 13, 1988	• Use of Support Services (Payload Processing)
			KSC/ VAFB	In Negotiation	• Use of SLC-2 and Support Services
			GSFC	December 22, 1988	• Use of Technical Transition Support
			OSO	April 28, 1989	• Use of OSO Resources, Principally GSFC, Code 500
MARTIN MARIETTA (Titan III)	October 1988	Use of Launch Support Services	KSC	March 16, 1989	• Use of Support Services (Payload Processing/ Encapsulation)
			MSFC	May 2, 1989	• Use of Acoustic Test Facilities
LTV (Scout)	November 1988	Use of Production Tooling, STE, GSE/ Launch Service Support	GSFC/ WFF	Draft in Work	• Use of Real Property • Use of Range Safety/ Range & Support Services
			LaRC	GSFC Concurrence Rev.	• Use of GSE, Production Tooling STE
			KSC/ VAFB	Preliminary Discussions	• Use of Facilities/Support Services
ORBITAL SCIENCES (Pegasus/ Taurus)	Final Signature Cycle - On Hold	Use of Launch Support Services/ Facilities	GSFC/ WFF	Draft in Review	• Use of Facilities/Support at WFF
			AMES/ DFRF	Draft in Review	• Use of Facilities/Support at DFRF/Use of NASA B-52
AMERICAN ROCKET (Industrial L.V.)	First Draft	Use of Launch Support Services/ Facilities	TBD	TBD	TBD
E' PRIME (E'PAL)	First Draft	Use of Support Services/Facilities	KSC	Preliminary Discussions	• Use of Facilities/Support Services at ETR
TRW (TBD)	First Draft	Use of Property/Services	GSFC/WFF	Preliminary Discussions	TBD
			SSC	Preliminary Discussions	• Use of Test Facilities

Table A-2. NASA ELV Commercialization Agreements as of June 1990

APPENDIX B

ELV PROCUREMENT DETAILS AND VEHICLE DESCRIPTIONS

AIR FORCE:

For the CELV program, Martin Marietta was awarded a ten-vehicle Titan IV contract. In addition, Martin Marietta was given a contract to modify eight Titan IIs. Following the Challenger and Titan accidents, the Titan IV program was expanded to provide 23 vehicles with west-coast launch capability and with launch rate capability increased from two to six per year.

The McDonnell Douglas MLV contract provides for the acquisition of 20 Delta II vehicles with unpriced options for additional vehicles through 1994.

The General Dynamics MLV II contract provides for the acquisition of two Atlas II vehicles with options for up to eight per year through 1995.

NASA:

Under the mixed fleet launch strategy, four Shuttle payloads were rescheduled for ELV launches. They are the Roentgen Satellite, Extreme Ultraviolet Explorer, Combined Release and Radiation Effects Satellite, and Mars Observer.

The 1988 launch services contract to General Dynamics was to support the launch of two firm and three optional NOAA GOES satellites. Other commercial launch services and launch vehicles being procured include:

- Small ELV: NASA plans to award an SELV launch services contract in 1990 for seven firm and three optional launches to support the scientific Small Explorer Program.

- Medium ELV: The MELV contract being negotiated with McDonnell Douglas will provide for launch services for three firm and twelve optional Delta II launches to support NASA scientific and technology applications spacecraft.

- Intermediate ELV: A proposal to provide launch services for the scientific Solar Heliospheric Observatory is currently under evaluation with a contract award targeted for the Spring of 1990. A request for proposals to procure launch services commercially to support the Mobile Satellite spacecraft is targeted for release in the Spring of 1990.

- Large ELV: NASA plans will require an average of one Titan IV per year from the Air Force beginning in 1995 to support major scientific planetary and observatory missions.

VEHICLE DESCRIPTIONS:

The General Dynamics Atlas family of vehicles is based on modifications of the NASA Atlas/Centaur vehicle introduced in 1967, which was an evolutionary development of the Air Force 1950s Atlas ICBM. The Atlas, a two and one-half stage vehicle, is powered by oxygen/ hydrocarbon (RP-1) engines; the Centaur is powered by oxygen/ liquid-hydrogen engines.

- Atlas I is an improved version of NASA's Atlas/Centaur compatible with a larger (14-foot diameter) payload fairing.
- Atlas II builds on the Atlas I configuration to provide increased performance capability -- most notably, increased booster engine thrust and lengthened propellant tanks.
- Atlas IIA is similar to Atlas II but incorporates an uprated RL-10 propulsion system and upgraded avionics.
- Atlas IIAS builds on Atlas IIA with the addition of four Castor IVA solid rockets for increased performance capability.

The McDonnell Douglas Delta II is an upgraded version of NASA's Delta launch vehicle which was originally derived from the Air Force Thor intermediate-range ballistic missile, with improved first and second stages and the addition of several small solid rocket motors. Delta II has two configurations; the first configuration has upgraded strap-on motors and the second configuration includes upgraded composite-case solid rocket motors. Both configurations are available in either two or three stages and include a 12-foot propellant tank stretch and a bulbous payload fairing.

The Martin Marietta Titan III launch vehicle is the company's variant of the Air Force Titan III/34D family first launched in 1966. It is based on a common Titan design concept featuring a two-stage, liquid-propellant,10-foot-diameter core vehicle with two strap-on solid rocket motors.

Titan IV is a non-commercial stretched, strengthened development of Titan III with a new payload fairing diameter designed to accommodate Shuttle-compatible payloads. Titan IV has three versions: one with no upper stage, one with an Inertial Upper Stage, and one with Centaur.

APPENDIX C

ACRONYM LIST

A&R	Automation and Robotics
AETB	Advanced Expander Test Bed
ALS	Advanced Launch System
BITE	Built-In Test Equipment
CELV	Complementary Expendable Launch Vehicle
CFD	Computational Fluid Dynamics
COMSTAC	Commercial Space Transportation Advisory Committee
CSTI	Civil Space Technology Initiative
CTP	Chemical Transfer Propulsion
DFRF	Dryden Flight Research Facility
DOD	Department of Defense
DOT	Department of Transportation
ELV	Expendable Launch Vehicle
EMA	Electromechanical Actuator
EMI	Electromagnetic Interference
ETO	Earth-to-Orbit
ETR	Eastern Test Range
GD	General Dynamics
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HCF	High Cycle Fatigue
ICBM	Intercontinental Ballistic Missile
IELV	Intermediate Expendable Launch Vehicle
KSC	John F. Kennedy Space Center
LaRC	Langley Research Center
LeRC	Lewis Research Center
LCF	Low Cycle Fatigue
LIDAR	Light Detection and Ranging
LOX	Liquid Oxygen
MELV	Medium Expendable Launch Vehicle
MLV	Medium Launch Vehicle
MSFC	George C. Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASP	National AeroSpace Plane
NOAA	National Oceanographic and Atmospheric Administration
O&M	Operations and Maintenance
OAET	Office of Aeronautics, Exploration and Technology
OMS	Orbital Maneuvering System

OSF	Office of Space Flight
OSO	Office of Space Operations
OSSA	Office of Space Science and Applications
P.L.	Public Law
RCS	Reaction Control System
SELV	Small Expendable Launch Vehicle
SOFI	Spray-on Foam Insulation
SPIP	Solid Propulsion Integrity Program
SRM	Solid Rocket Motor
SSTAC	Space Systems Technology Advisory Committee
STE	Special Test Equipment
R&D	Research and Development
R&T	Research and Technology
TBD	To Be Determined
TDRS	Tracking and Data Relay Satellite
TPS	Thermal Protection System
VAFB	Vandenberg Air Force Base
WFF	Wallops Flight Facility

SINGLE SOURCE VENDOR SURVEYS

REDESIGNED SOLID ROCKET MOTOR

The survey identified 26 items having a single source which are considered to be a potential concern. Of these, 16 are of limited availability where there is no other source for a similar item. For the remaining 10, similar items are available, but qualification would be required. The single sources involve 19 different vendors. Development of second sources for four of the items is already in progress and the remainder are under consideration. Costs to develop second sources vary from $14.6M for another carbonizable rayon to $10K for cable insulation.

SOLID ROCKET BOOSTER

The survey identified 84 material/component single source items, none of which is an immediate threat. Of these, 38 are material items of limited availability, of which nine are of potential concern and for which development of alternate suppliers, or plans for stockpiling, are already in progress. The survey also identified 46 components procured from single sources. These are reusable items and no new procurements are planned in the near future. If a supplier were to be lost, adequate time would be available to develop an alternate source for refurbishment or production. Therefore, development of a second source for these items is not recommended.

SPACE SHUTTLE MAIN ENGINE (SSME)

There are no vendors for the SSME Project that present an immediate failure threat to the Space Shuttle operations. However, there are a number of single sources which could adversely affect the SSME operations if any of the companies' production were stopped due to an unplanned event and development of a second source were required. The survey identified 86 items having a single source availability which were considered to be of potential concern. The analysis concluded that by stockpiling a supply of components, piece parts and raw materials, development of second sources could be avoided at this time. Approximately $13 million would be required to provide program protection for the items identified.

EXTERNAL TANK

There are no single source suppliers for the External Tank Project that present an immediate strategic threat. The survey identified 10 single source components/material items which are of potential concern. Of these, four have sufficient inventory to support the approved flight rate for the next two years, which is the lead time required for development of a second source. The remaining six are single source items. Costs to stockpile these items vary from $0.7M to $11.2M.

ORBITER

There are no single source vendors for the Orbiter or Government-furnished equipment (GFE) hardware items reviewed that present an immediate strategic threat that would significantly affect support of the approved flight rate. The survey identified 40 orbiter components/materials as potential areas of concern. Of these, 15 were categorized as limited availability (single source) and 25 universal availability (universally-available, but with only one certified source). The study made recommendations ranging from purchasing lifetime supplies of certain items to developing second sources. Additional recommendations included consideration of temporary workarounds for parts if they were to become unavailable, redesign to use different parts, and creation of procedures for extending the useful life of existing hardware. None of the hundreds of GFE items are from single source vendors that could cause an immediate threat.

LIQUID PROPELLANTS AND OTHER FLUIDS

A survey of liquid propellants and other fluids considered to be of potential concern identified 12 commodities having limited availability due to single sources, production restrictions and/or a history of supply problems. Development of second sources, increases in stockpiled quantities, and/or modification of facilities to increase supportability are under consideration. Investigation into substitutes for Solvent-113, the production of which is limited by the Environmental Protection Agency, is continuing, but no one compound looks promising for all applications.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: ME

JUL 11 1990

TO: Johnson Space Center
Attn: GA/Deputy Director, Space Shuttle Program

FROM: M-7/Director, Space Shuttle

SUBJECT: Review of Single Sources of Critical Space Shuttle System Components and Materials

In FY 1989, NASA began a review of the single sources for essential industrial materials for national space programs at the request of the National Security Council. At the time, the Space Shuttle projects were requested to initiate a survey of element manufacturing and support to identify items procured from a single source. Subsequent direction requested evaluation and recommendations to mitigate the vulnerabilities resulting from these single sources.

We have received the results of this effort from the projects. Where a project may recommend development of a second source, stockpiling, or other course of action which involves a budgetary adjustment, a change request must be brought to the Program Requirements Control Board (PRCB) for disposition. In addition, where a project makes a major change or new procurement, such as a redesign or product improvement, the prime contractor will provide an assessment of alternatives to a single source for review by the project.

For this activity to be fully effective, it needs to be an ongoing process. Therefore, please initiate direction to the projects to update these reports on an annual basis. Recommendations which involve budgetary impacts can then be submitted with the POP or through the PRCB depending on whether it is far or near term.

The results of this activity will be most beneficial in understanding the vulnerabilities present from single sources of critical hardware and materials. This should provide assurance that the proper actions are being taken to maintain these vulnerabilities at acceptable levels and to avoid potentially severe program disruptions.

Robert L. Crippen

cc:
M/Dr. Lenoir
KSC/MK/Mr. Shaw

Enclosure 2

NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

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Committee on Science, Space
and Technology

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Reply to Attn of: L:JJM:jl

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

In House Report 101-226, which accompanied H.R. 1759, the NASA Multiyear Authorization Act of 1989, NASA was directed to submit to the House Committee on Science, Space and Technology and the Senate Committee on Commerce, Science, and Transportation a draft long-range plan on the management of the Space Shuttle Orbiter production line through the life of the program.

In compliance with this requirement, I am forwarding an interim report on the planning effort. It is the Agency's intent to complete a detailed plan for retaining long-term critical skills and facilities as well as an analysis of potential requirements for additional orbiters by October 1990.

If you wish to discuss the matter further, I would be pleased to meet with you or your staff.

Sincerely,

Martin P. Kress

Martin P. Kress
Acting Assistant Administrator
for Legislative Affairs

Enclosure

cc: Honorable Robert S. Walker

REPORT ON THE SPACE SHUTTLE ORBITER PRODUCTION PLAN

In House Report 101-226 accompanying H.R. 1759, the NASA Multiyear Authorization Act of 1989, the Committee expressed great concern about the lack of a comprehensive long-term policy on how to manage the production line that is used to manufacture Space Shuttle Orbiters.

Accordingly, the Committee directed NASA to undertake whatever studies and analyses are required to provide for a long-range plan on how to manage the production line for Space Shuttle Orbiters throughout the life of the Space Shuttle program. The Committee directed the Agency to formulate a draft on such a plan and submit it to the Committee on Science, Space and Technology of the House of Representatives and the Committee on Commerce, Science and Transportation of the Senate. The Committee also suggested that NASA consider the following options in the course of developing the plan:

(1) Over the next few years, build at the most efficient rate possible all of the Orbiters that are expected to be needed throughout the life of the Space Shuttle program and then shutdown the production line:

(2) Keep the production line open throughout the life of the Space Shuttle program by continuously building Orbiters at a slow rate that is calculated to provide replacement Orbiters at a pace that will roughly equal the rate at which they will either wear out or be lost in accidents:

(3) After building a replacement set of structural spares, shutdown the production line and only reopen it if future accidents occur at a rate that makes this necessary.

Consistent with the Committee's direction, a study is underway which will lead to a long-range plan for NASA orbiter production capability requirements and maintenance. In response to the Committee's request for a draft of this plan, the following is submitted as a report of the status and interim findings of the plan effort, organized in the context of the Committee's suggested alternatives.

The first option, which the Committee suggested, to produce all of the orbiters expected to be required for the life of the Shuttle program, would be difficult to institute because the life of the Shuttle program has not been determined. There currently is no future or follow-on vehicle planned which would establish a boundary for the anticipated life of the current vehicle design. The baseline plan is to use the orbiter for the foreseeable future to meet the nation's manned space flight requirements, and we are actively pursuing programs to insure the orbiter's ability to accomplish this. In addition to the uncertainty as to the length of time that the orbiters will be operational, there is uncertainty on how many orbiters would be required during that period. Although this alternative is the least expensive over the long-term to procure a given number of orbiters, it is questionable that the "right" number of orbiters would be built. In addition, this option would be most expensive in the near-term.

The second option was to keep the production line open throughout the life of the Shuttle program and slowly build additional vehicles. This closely resembles the orbiter build program to date with its cycle of building structural spares combined with the later completion of the vehicles. This process can be tailored to produce vehicles at a rate which is consistent with our needs while maintaining the contractor capability required for both the operations and production programs.

The third option offered by the Committee is to complete the replacement structural spares and then shut down the production line, only reopening it to replace orbiters lost in future accidents. This option involves higher risk since it offers no margin to support orbiter anomalies, extended downtimes, or implementation of upgrades. If orbiter vehicles are taken out of service for extended periods of time for significant modifications or upgrades, either the planned flight rate will have to be reduce or an additional orbiter will be required to support the manifest during that period. Shutting down the production line and not maintaining capability to produce orbiters would require that missions be cancelled during the four-year period it takes to build another orbiter, and it would significantly increase the cost of building a new orbiter.

The ability to produce orbiter vehicles is dependent upon a variety of skills at the prime contractor (Rockwell) and at numerous subcontractors. Although the Endeavour will be delivered to the Kennedy Space Center in May of 1991, most of the critical subcontractors will complete their deliveries by this fall. After delivery of Endeavour, the Palmdale facility where orbiters are assembled and checked out will stay in use through FY 1991 with the planned Extended Duration Orbiter (EDO) modifications to OV-102. Likewise, after delivery, some of the key subcontractors will be retained through hardware purchase and capability retention contracts funded by the Kennedy Space Center logistics program. The overall orbiter logistics effort is approximately $200 million per year of which approximately $100 million is applicable to orbiter production capability.

Additionally, the production of a new set of structural spares to replace the ones used to build Endeavour began this fiscal year. This program will serve to maintain some of the critical manufacturing capability at Rockwell and the structural subcontractors for the next four years.

Also, the Rockwell orbiter production contract, through design changes and vehicle modifications, maintains a limited design and manufacturing capability at Rockwell and a select number of subcontractors. These changes are driven by obsolescence, flight failures, safety or performance improvements, etc. There is also ongoing production activity to supply the external tank disconnects for each mission.

And last, the Rockwell sustaining engineering contract performs operations support for the life of the orbiter flight program. This effort is the core of engineers with basic knowledge of the orbiter systems and analytical skills to evaluate specific conditions for each mission. The skills for subsystems, laboratories, and product assurance are also required to support a production program. This effort, which is supported by approximately 720 engineers, is important to orbiter production capability.

Some manpower skills and facilities will not be retained in the above efforts. Some subcontractors are now making their final deliveries for Endeavour and their final deliveries for logistics. Additionally, certain skills at the Rockwell Palmdale and Downey facilities will be reduced prior to the end of FY 1991.

A study has been initiated to analyze the many facets of the production requirements and capability retention issue. This will include a full evaluation of the future flight rate demand and of the current fleet capability. Major planning factors to be considered includes combating obsolescence, insuring structural viability with aging vehicles, and protecting against an incident removing a vehicle for a significant period of time. Also, an in-depth review of each contractor's logistics and production plan is in work, as is a review of all critical manpower. The results of the above studies will form the basis for determining what additional vehicles will be required and when they will be needed.

In summary, NASA is continuing to study options for meeting future national requirements with the orbiter fleet. Important factors being considered include maintaining planned flight rates, protecting key manufacturing and design capabilities, and minimizing program costs. A detailed plan for retaining long-term critical skills and facilities will be completed this September, as will our analysis of the timing of procurements of additional orbiter(s).

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

August 29, 1990

Honorable Robert A. Roe
Chairman
Committee on Science,
Space and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

On June 27, 1990, NASA implemented the Hubble Space Telescope Contingency Plan in response to the observed spherical aberration in Hubble. NASA is committed to providing Congress with timely information on this subject as it becomes available.

Given the programmatic implications of this problem, I would like to inform you of our plans. A key element of our response to the problem is associated with producing the second Wide Field/Planetary Camera (WF/PC II) with modified optics that will fully correct for the aberration in the Hubble mirror. The key elements in developing the correction will be to:

- precisely characterize the prescription of the Hubble mirror to the limits of WF/PC II sensitivity on a schedule to support the planned service mission in 1993;
- modify the existing WF/PC II mirror simulator so that it produces the exact flaw of the on-orbit mirror; and,
- conduct rigorous verification and testing of both the ground simulator and the instrument to guarantee that only the existing flaw has been duplicated.

The cost for the activities described above is expected to be $3.4 million in FY 1990. This funding will support the initial optical analysis and long-lead procurements. Funding to support this unanticipated work has been identified within the current FY 1990 Physics and Astronomy Mission Operations and Data Analysis (MO&DA) budget, and can be made available through the deferral of non-time critical procurements within Gamma Ray Observatory MO&DA enabled as a result of the delay in the launch.

I will keep you informed as to future development

Sincerely,

James R. Thompson

Richard H. Truly
Administrator

cc:
Honorable Robert Walker

Roe

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: L:DL:brb

SEP 5 1990

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed, for the information of the Committee, is a copy of the report sent to the Speaker of the House pursuant to Public Law 101-189, Section 3131. This report responds to the amended Steveson-Wydler Act concerning technology transfer and intellectual property.

Sincerely,

Martin P Kress

Martin P. Kress
Acting Assistant Administrator
for Legislative Affairs

Enclosure

cc:
Honorable Robert S. Walker

NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546
Office of the Administrator

AUG 15 1990

Honorable Thomas S. Foley
Speaker of the House of Representatives
Washington, DC 20515

Dear Mr. Speaker:

Public Law 101-189, the FY 1990 Department of Defense Authorization Act, amended Section 11(b) of the Stevenson-Wydler Technology Innovation Act of 1980, by repealing the agency waiver provisions pertaining to agency technology transfer requirements specified therein. In lieu of the waiver mechanism, each Federal agency is directed to prepare and submit to the Congress an annual report describing its technology transfer program for the preceding year and the agency's plans for conducting its technology transfer function for the upcoming year. Such reports are to include plans for securing intellectual property rights for laboratory innovations with commercial promise and plans for managing such innovations so as to enhance the competitiveness of United States industry.

I am pleased to transmit to you the first annual report of the National Aeronautics and Space Administration required by the amended Stevenson-Wydler Act. The report is for the period 1989-1990 and is divided into two sections, one concerning technology transfer and the other concerning intellectual property.

Sincerely,

Richard H. Truly
Administrator

Enclosure

A REPORT TO CONGRESS

TECHNOLOGY TRANSFER REPORT

Fiscal Year 1990

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON, D.C.

[This report is submitted in accordance with provisions of Public Law 101-189, dated November 29, 1989, amending Section 11(b) of the Stevenson-Wydler Technology Innovation Act of 1980 (15 U.S.C. 3710(b))]

PREFACE

On November 29, 1989, Public Law 101-189, the FY 1990 Department of Defense Authorization Act, amended Section 11(b) of the Stevenson-Wydler Technology Innovation Act of 1980, by repealing the agency waiver provisions pertaining to agency technology transfer funding requirements specified therein. In lieu of the waiver mechanism, each Federal agency is to prepare and submit to the Congress an annual report describing its technology transfer program for the preceding year and the agency's plans for conducting its technology transfer function for the upcoming year. Such reports are also to include plans for securing intellectual property rights in laboratory innovations with commercial promise and plans for managing such innovations so as to enhance the competitiveness of United States industry.

This report presents to the Congress the accomplishments and plans concerning such activities of the National Aeronautics and Space Administration (NASA) for the period 1989-1990. The report is divided into two sections:

Section I:	Technology Transfer and Utilization
Section II:	Patents and Intellectual Property

Since this is the first annual report of its kind submitted to Congress, it includes an in-depth description and discussion of the basic policies, procedures, and organization involved in carrying out the agency's technology transfer and intellectual property programs. This approach is deemed appropriate in order that the preceding year's efforts, as well as plans for the upcoming year, may be put into context. It is anticipated that with this in-depth presentation as a baseline, subsequent annual reports will focus on specific accomplishments for the past year, and plans for the year ahead.

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SECTION I

TECHNOLOGY TRANSFER AND UTILIZATION

INTRODUCTION

The wealth of aerospace technology generated in the course of NASA research and development programs constitutes an important national resource. Technology resulting from the agency's scientific and engineering advancements can be reused to develop new products and processes to the benefit of the nation's economy. While technology transfer does occur naturally in some cases, the process frequently requires active and aggressive efforts to assure broader awareness of the potential benefit that new technological advances offer for commercial use.

Since 1962, the National Aeronautics and Space Administration (NASA) has carried out an active and highly visible technology transfer effort through its Technology Utilization Program. This program was created in response to the Congressional mandate contained in the National Aeronautics and Space Act of 1958, which required the agency "to provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

Over the past twenty-eight years, the NASA Technology Utilization Program has established an effective array of mechanisms to promote the use of aerospace technology in the public and private sectors of the nation's economy. This report describes these mechanisms, provides information on last year's accomplishments and summarizes program plans for the year ahead.

I-1. TECHNOLOGY TRANSFER FUNCTIONS

NASA's technology transfer program has two fundamental aspects or functions:

(1) Technology Access and Information Dissemination in which existing technologies, described in written documents and reports, are matched with articulated needs of potential users; and,

(2) Technology Applications in which adaptive engineering of existing technologies is supported through joint-funded projects or cooperative agreements.

In both of these functions the creators of new technology (i.e., NASA field center and contractor scientists and engineers) work with potential users, in either public or private sector organization.

The technology transfer process is generally triggered in one of two ways: (a) new technologies developed for government purposes are made available for transfer (i.e., Technology Push), or (b) potential users define problems or technological interests which lead to a search for the most appropriate and relevant technologies to satisfy such needs (i.e., Demand Pull). The Technology Access and Information Dissemination program function is characteristic of the former, whereas the Technology Applications function is an example of the latter.

I-2. TECHNOLOGY ACCESS AND INFORMATION DISSEMINATION

Scientific and engineering advancements resulting from NASA research and development programs are the primary resource base of NASA's Technology Utilization Program. There are three (3) distinct elements which make up this resource base:
(1) the NASA scientific and technical information computerized database, which contains summaries of all NASA and NASA contractor technical reports generated as a result of NASA R&D programs and projects; (2) the NASA patent portfolio, containing all inventions in which NASA has either filed patent applications or patents have been issued; and, (3) reports of new technology (i.e., inventions, discoveries, improvements or innovations) issued in accordance with Section 305(b) of the Space Act of 1958.

While the responsibility within NASA for the management of resources (1) and (2) above rests with the Scientific and Technical Information Division and the Office of General Counsel for Intellectual Property, respectively, the responsibility for the reporting of new technology and the administration thereof lies with the Technology Utilization Division, Office of Commercial Programs. These three organizations work cooperatively to provide the basis of NASA's technology transfer efforts.

1. New Technology Acquisition and Evaluation

Each NASA field center has a Technology Utilization Office (TUO) which serves as the center's focal point for technology transfer. (The TU Office at each center functions as that laboratory's Office of Research and Technology Applications (ORTA) as required under P.L. 96-480.)

The basic responsibility of the Technology Utilization Officer is to stay abreast of research and development activities at his center that have significant potential for generating transferrable technology. He makes certain that the center's professional personnel identify, document and report new technology developed in the center's laboratories. He also monitors the center's R&D contracts to see that NASA contractors similarly document and report new technology, as required by law. New technology, so reported is reviewed by the center Patent Counsel in order to determine NASA interests in patent filing. Concurrently, the TUO evaluates the new technology for its technical significance and commercial potential.

Last year, nearly 2,300 new technology reports were received, screened and evaluated agencywide. This represents an approximate 15% increase over the previous year.

New technology acquisition was strengthened considerably in 1989 through the deployment of the Technology Utilization Network System (TUNS), a series of microcomputer-based area networks and workstations located at NASA field center TU Offices. The system has materially improved the process for new technology identification and R&D contract monitoring. In the upcoming year, continued emphasis will be placed on this important function in order to assure full reporting by NASA and NASA contractor technologists.

2. Technology Transfer Publications

New scientific and engineering advances that have significant commercial or other secondary use potential are then published and disseminated to U.S. industry through NASA Tech Briefs (NTB), a monthly periodical. NASA Tech Briefs now reaches over 185,000 scientists, engineers and businessmen throughout the nation. This represents a dramatic growth in readership from 75,000 in 1985 when NASA privatized the publication. Last year alone, the number of NTB subscribers grew by nearly 20,000 readers which underscores the importance that American industry places on this source of new technology.

Interested readers can obtain additional technical information, called Technical Support Packages (TSP), announced in NASA Tech Briefs. Last year NASA received over 100,000 industrial requests for this supporting documentation. Requests for TSPs frequently lead to discussions between NASA/NASA contractor technologists regarding specific advancements and their possible commercial applications.

A summary of NASA technology transfer publications activity is included in Appendix A-1.

3. Nationwide Technology Transfer Network

The NASA-developed nationwide technology transfer network is designed to provide U.S. industry with potential solutions to industrial problems based on rapid access to existing advanced technologies. This network is comprised of ten (10) Industrial Applications Centers (IACs), regionally disbursed throughout the nation. Since 1987, IACs have entered into agreements with 43 States and Puerto Rico to establish IAC Affiliates, which function as geographical extensions of the IAC network, working primarily through State university-based industry technical assistance centers, small business assistance centers, and similar organizations. A listing of the NASA Industrial Applications Centers and their Affiliates are provided in Appendix A-2.

The NASA Industrial Applications Centers and the Affiliates, which represent a major component of the NASA TU Program, are organized to promote and stimulate industrial interest in advanced technologies emanating from NASA as well as other government and private sector sources. These centers are mostly university-based which cultivate strong ties with industrial clients, assist them in identifying company problems or needs, and engage in problem-solving activities through computerized access to over 500 scientific and technical information public and private databases available worldwide, as well as technical experts in NASA and other government laboratories engaged in current research and development activities that may have broad commercial potential. Integral to IAC products and services available to industry are added-value studies and analyses which match specific known technological resources with client problems and interests. Examples of recent IAC technology transfer achievements are described in Appendix A-3.

The network has developed close working relationships over the past several years with the Federal Laboratory Consortium (FLC) and its member laboratories. These relationships have further strengthened the ability of the network to stimulate the transfer of all Federally-developed technology to enhance productivity and competitiveness of U.S. industry.

During the past year, NASA IACs conducted over 50,000 information searches for nearly 6,000 industrial clients, and conducted 12,000 value-added studies or analyses in connection with specific problems identified by industry. This reflects an increasing demand by U.S. industry for access to externally-developed technologies which is higher today than ever before. Our plans for the coming year will assure that the NASA technology transfer net~~work has~~ the capability to meet this increasing demand.

4. National Technology Transfer Center (NTTC)

On behalf of the federal government, NASA has undertaken a FY 1990 Congressional initiative to develop and establish the National Technology Transfer Center (NTTC) at Wheeling Jesuit College, Wheeling, West Virginia.

The NTTC mission is to enhance the ability of the United States to compete by facilitating the transfer of federally-sponsored R&D to the U.S. private sector. In fulfilling its mission, the NTTC will utilize and augment the nation's technology transfer and utilization activities and programs, including the Federal Laboratory Consortium, the NASA Technology Transfer System, and other federal and state programs involving technology transfer and utilization. To accomplish the NTTC mission, NASA has begun a phased (FY 90 - FY 95) development program, now approaching its initial implementation phase, to fully establish the NTTC as a national focal point for accessing federal technology transfer resources and networks and as a catalyst and leader in accelerating and expanding U.S. commercial sector utilization of federal technologies. The NTTC focus on improving technology access is strengthened by supporting NTTC functions directed toward the use and enhancement of existing technology transfer resources nationwide and the active stimulation through national outreach activities of U.S. private sector awareness of and demand for available federal technologies.

In FY 1990, drawing upon the extensive experience and expertise of its Technology Utilization Program and a Congressionally-directed preliminary NTTC definition/design study reported to Congress in FY 1989, NASA continued planning, research and definition activities in preparation for initiating NTTC implementation in early FY 1991. As currently planned, the NTTC, following a regional demonstration of selected NTTC capabilities, will achieve initial NTTC nationwide operations in late 1992. The final phase of the development program involves the incremental build-up of NTTC capabilities and activities, culminating in a fully operational NTTC in late 1995.

5. Computer Software Management and Information Center (COSMIC)

The NASA-sponsored Computer Software Management and Information Center (COSMIC), located at the University of Georgia, is a special center created for the dissemination of NASA-developed computer programs to industry. Since 1966, COSMIC has provided a successful mechanism for technology transfer and has achieved a level of operational stability in terms of its software inventory as well as the size of its industrial client base. COSMIC actively promotes the availability of its program holdings to industry through selective advertising and participation in industrial trade shows.

Recent actions by NASA have been designed to further strengthen the role of COSMIC as a software clearinghouse for industry. In 1989, NASA entered into an agreement with the Federal Laboratory Consortium (FLC) that permits COSMIC to exchange software on a 3 for 1 basis with any Federal laboratory at no cost to either organization. This Exchange Program not only provides Federal laboratories with an established outlet for the transfer of its software to industry, but at the same time, provides broader access to software developed by NASA but all Federal R&D organizations as well. This year, NASA has also authorized COSMIC to expand this effort beyond the Federal laboratories to other Universities that may also wish to participate in the software Exchange Program.

Plans for COSMIC in the coming year include the development of a policy designed to facilitate access to "research codes" (computer programs designed for research purposes, but not fully developed) in order to move new technology into the private sector more rapidly. Additionally, COSMIC's catalog will be available for interactive on-line searching, and COSMIC will expand its role in hosting NASA User Group meetings for selected software products. COSMIC has coordinated the NASTRAN Users' Colloquium since 1982, and in August 1990, COSMIC will help coordinate the first C Language Integrated Production System (CLIPS) User Group conference in support of the Johnson Space Center.

6. AdaNET Program Development

In 1987, NASA prepared a plan to create a national facility called AdaNET to increase U.S. productivity, economic growth and competitiveness through the development of a lifecycle repository for Ada language software engineering products, processes, interfaces, and related information services. This plan was developed in cooperation with the Department of Defense and the U.S. Department of Commerce.

The AdaNET facility will support software engineering by identifying and storing reusable software lifecycle components -- e.g., concept documents, specifications, software code, and performance date -- and making those components available to engineers. Where engineering principles are applied and components are reused, software development productivity may be increased by as much as eighty percent (80%). This is analogous to the historic introduction of interchangeable parts and assembly-line techniques in U.S. manufacturing.

In 1989, AdaNET completed Phase I and began Phase II planning and development. Phase I consisted of the deployment of a second-generation prototype software engineering computer network and repository, AdaNET Service Version 2 (ASV2); operation and analysis of ASV2 with a national community of users; acquisition, catalogue and population of ASV2 with lifecycle software components and information from the Army, NASA and other government and commercial sources; strengthening of technical and management capabilities through industry team-building; software engineering market research and analysis; and related technology transfer activity. Based upon the Phase I experience, AdaNET formulated a 24-36 month plan for next phase development, operation, and analysis. The plan will result in a prototype AdaNET network and repository with considerable capabilities. Following Phase II, NASA will assess options for deployment of a production quality AdaNET.

Next year's plans include four major activities: a) Requirements Definition; b) Requirements Analysis and System Development; c) System Operation; and d) Evaluation. Included in these major activities are: market research; identification of potential AdaNET users in industry and government; establishment of AdaNET special interest groups; upgrades to AdaNET software; new software development, including development of a sophisticated reusable software library; identification of government sources for software components; adding software components and related information to AdaNET; upgrades for the AdaNET computer center in Dellslow, West Virginia; software engineering research; analysis of legal issues involved in reuse; operations and prototype analysis; and user support.

7. Conferences, Seminars and Trade Shows

All participants in the NASA Technology Transfer Network, including NASA field centers, Industrial Applications Centers, and COSMIC exhibited or made presentations in a wide spectrum of conferences, seminars and industrial trade shows during 1989. Such efforts are designed to create broader awareness of the NASA network and the technology transfer products and services that are available for industrial access. A representative listing of conferences, seminars and trade shows in which the network participated in last year is shown in Appendix A-4.

This next year, NASA will step up its efforts to advance technology transfer and promote greater interaction with the non-aerospace sector of U.S. industry. In a major planned event, NASA will sponsor a two-day conference in November, 1990 in Washington, D.C., to showcase emerging technologies for use by industry. The goal of **Technology 2000**, planned as an annual event, is to support the national technology transfer program by laying the groundwork for the effective use of emerging technologies being planned and developed for future NASA missions, and provide American industry an overview of current NASA R&D projects in which near term technological advancements may have high commercial potential. Approximately 2000 executives and R&D directors from non-aerospace corporations are expected to attend. Co-sponsors of the conference are NASA; the Technology Utilization Foundation, a non-profit organization which will manage the show; and, Associated Business Publications, Inc., the publisher of NASA Tech Briefs.

I-2. TECHNOLOGY APPLICATIONS

Another major function of NASA's Technology Utilization Program is Technology Applications in which NASA collaborates with industry and public sector organizations to reengineer aerospace technology for use in terrestrial applications.

1. Technology Applications Team

To facilitate the development of these collaborative efforts, NASA has established an Applications Team, consisting of scientists and engineers from a wide range of disciplines which provides an active interface with NASA field centers, industry and Federal and State agencies to define significant technology needs and identify possible solutions based on existing NASA technology. Once a problem is defined and documented, the problem statement is circulated to each NASA field center Technology Utilization Officer (TUO) who, in turn, enlists the aid of NASA scientists and engineers to determine possible solutions based on current aeronautics and space technology.

The possible solution is screened by the problem originator and team members to assess the probability of technical and commercial success. A mutual decision is then made whether it is in the best interest of NASA, the mission agency and industry to go forward with the technology transfer project.

2. Applications Engineering Projects

Once a probable solution is agreed upon, NASA joins with industry and other agency participants in the development of an Applications Engineering Project. Industry participation is encouraged through cooperative agreements or joint endeavor contracts. Project tasks, schedules and milestones are carefully defined, and responsibilities, both technical and financial, are delineated and agreed upon prior to project implementation. The 1Technology Utilization Officers, the Applications Team and the NASA Patent Offices work with all outside parties to resolve legal and technical issues and minimize barriers to participation.

At present, NASA is conducting nearly 60 active projects in conjunction with other mission agencies at the Federal and State levels. These projects span a wide range of areas of public concern -- health and medicine, environment, public safety, industrial manufacturing, and education. Current projects are listed in Appendix B-1, and several examples are described in Appendix B-2 which illustrate last year's accomplishments.

This next year, NASA will continue to focus its applications engineering effort to address problems confronting correctional institutions across the nation. This effort was initiated in 1989 in an interagency agreement between NASA and the National Institute of Corrections (NIC) in the Department of Justice. Typical among the problems in correctional facilities that may be addressed by NASA technology are the following: (a) perimeter security and control; (b) contraband detection ; and, (c) improve systems to enhance adult literacy. Next year, NASA also plans to emphasize applications of aerospace technology to identified problems in the fields of environment and education.

SECTION II

SECURING AND MANAGING INTELLECTUAL PROPERTY RIGHTS

This Section addresses NASA's intellectual property program as an adjunct to its technology transfer function. It includes the efforts of the preceding year (FY 1989) as well as plans in the upcoming year (FY 1991) for securing intellectual property rights in laboratory innovations with commercial promise and NASA's plans for managing such innovations so as to benefit the competitiveness of United States industry.

II-1. INTELLECTUAL PROPERTY RIGHTS & TECHNOLOGY TRANSFER

NASA views its intellectual property program as an important and complementary adjunct to its technology transfer activities. Thus NASA administers its intellectual property program so as to secure, whenever practicable and appropriate, intellectual property rights in its laboratory innovations to the maximum extent permissible under law. The objective is to make rights available, through licensing, as an incentive for United States industry to commercialize such innovations. Such licenses may be exclusive, partially exclusive, or nonexclusive, and are usually royalty bearing. When legally permissible, a percentage of the royalties is distributed to the innovator to encourage further participation in the technology transfer process.

1. General Considerations

The legally recognizable intellectual property rights that may be secured and applied to the technology transfer process are patent rights, copyrights, and rights analogous to common law trade secret rights. As a practical matter the latter two types of rights are not available for innovations made at Federally-operated (as distinguished from contractor-operated) laboratories, except in some very limited circumstances. In addition, under present policies and regulations, agencies normally do not acquire the right of ownership in trade secrets and copyrights from contractors. Thus the intellectual property rights to be secured are, in the main, patents on either inventions made by NASA employees at the NASA-operated laboratories (Field Centers) or on inventions for which NASA may have acquired title from a contractor. The management thereof consists of licensing (preferably under exclusive, royalty-bearing licenses) for commercial use and the monitoring of a licensee's efforts to this end to assure that the licensed invention is not suppressed or abandoned.

Such licenses, however, cannot be properly managed for the benefit of the competitiveness of United States industry unless an agency is also willing and able to seek enforcement of the patent, either itself or in conjunction with a licensee, against unlicensed or infringing use. Intrinsically, efforts to enforce will precipitate challenges to the validity of the patent. The issues, problems, and resources involved in this process are just beginning to evolve and be understood since the enactment of the Federal Technology Transfer Act of 1986 (and which the amendment thereto by Pub. L. 101-189 to require this Report will bring into sharper focus). Experience is beginning to show that merely obtaining a patent, or merely executing a license, does not constitute adequate management of the program.

As to securing copyright for innovations made by Federal employees at Federally-operated laboratories, this is now precluded by 17 U.S.C. 105. There are reviews underway by both the Legislative and Executive Branches that may result in a change in the law in that respect -- particularly in regards to computer software -- but the prospects for change are, at present, problematical. Should such a change occur, however, an infrastructure will have to be set up to secure protection and to manage the copyrighted innovations involved. While the process may not be as complicated and time consuming as obtaining and licensing patents, some of the same issues will arise, and some additional expertise and resources will be necessary in order to effectively produce results beneficial to competitiveness of United States industry.

As to securing intellectual property rights to innovations in a manner analogous to common law trade secret protection, the essential need is the ability to maintain information which divulges the innovation "in confidence," and to prevent its unauthorized disclosure and use. This prerequisite is something that is presently legally and culturally very difficult, if at all possible, in connection with activities at a Federally-operated laboratory. At a minimum, there must be a generic exemption to the Freedom of Information Act to authorize agencies to withhold information having commercial promise from unrestricted public disclosure -- authority which neither NASA nor any other agency now has.

While Sec. 3133(a)(7) of Pub. L. 101-189 does provide authority for agencies to withhold from public disclosure certain information developed at a Government-operated laboratory as the result of a cooperative research and development agreement entered into pursuant to the authority of Section 12 of the Stevenson-Wydler Technology Innovation Act of 1980, this authority is very limited. For example, for mission-oriented agencies such as NASA, innovations produced under such agreements are probably minimal compared to innovations produced as the result of generic in-house research and development activities conducted at their laboratories. Also, since NASA currently enters into cooperative research and development activities under the direct authority of sections 203(c) (5) and (6) of the National Aeronautics and Space Act of 1958, as amended (42 U.S.C. 2473 (c) (5) and (6)) (Space Act agreements) rather than the authority of Section 12 of the Stevenson-Wydler Technology Innovation Act, this new withholding authority is not available to NASA even though such Space Act agreements are virtually identical to those authorized by Section 12 of the Stevenson-Wydler Technology Innovation Act and are intended to produce the same results in fostering technology transfer and commercial use.

2. Organizational Structure

NASA's intellectual property program, including the acquisition and licensing of patents, and the distribution of royalties received therefrom, is administered by the General Counsel. Most functions are delegated to the Associate General Counsel -- Intellectual Property, and many have been redelegated to the Patent Counsel or Intellectual Property Counsel at the NASA Field Centers. The Associate General Counsel also provides functional guidance to Patent Counsel or Intellectual Property Counsel for these activities. Under such delegation and guidance, securing of rights and obtaining patents are a primary responsibility of the Patent or Intellectual Property Counsel at the Field Centers. The licensing activities, including the managing of the licenses, are carried out by the Director of Patent Licensing at NASA Headquarters, who reports to the Associate General Counsel -- Intellectual Property. Such licensing activities are carried out in cooperation with the Patent Counsel or Intellectual Property Counsel at the Field Centers. Royalties are collected and distributed under the supervision of the Director of Patent Licensing. NASA's policies regarding the securing of patents on employee inventions, and the distribution of royalties received therefrom, are set forth in NASA Management Instruction (NMI) 3450.2B (Appendix C). NASA's policies and procedures for the licensing of NASA-owned inventions are set forth in NMI 5109.3B (also published in the Code of Federal Regulations at 14 CFR 1245.2) (Appendix D).

3. Scope of Coverage

This Report covers intellectual property rights relating to innovations for which NASA has acquired right of ownership (title) from its employees or from its contractors, for activities at the following NASA Field Centers (laboratories):

Ames Research Center
Goddard Space Flight Center
Johnson Space Center
Kennedy Space Center
Langley Research Center
Lewis Research Center
Marshall Space Flight Center
NASA Resident Office - Jet Propulsion Laboratory

It does not separately cover the John C. Stennis Space Center in that the center has no Patent or Intellectual Property Counsel. Rather, intellectual property rights matters arising at Stennis are handled by the Marshall Space Flight Center (MSFC) and are included in the report statistics reported for MSFC.

This Report also does not include innovations made at the Jet Propulsion Laboratory (JPL) for which the California Institute of Technology (Caltech) has retained title. That is because intellectual property rights arising from activities at JPL are treated the same as for similar activities of any independent contractor. Thus, under the terms of the contract with Caltech, rights to inventions made at JPL are allocated in accordance with the provisions of 35 U.S.C. 200 et. seq. In addition, data rights, including copyright and rights to computer software, are determined pursuant to provisions in the contract with Caltech, consistent with Subpart 27.4 of the Federal Acquisition Regulation and the NASA Supplement thereto. Whenever Caltech acquires any intellectual property rights under these provisions, they are secured and managed by Caltech the same as any independent contractor; they are not secured and managed by NASA. When intellectual property rights are acquired by NASA under these provisions (i.e., Caltech has not elected rights), they are secured and managed by NASA the same as rights acquired from any independent contractor.

II-2. INVENTIONS, PATENTS, & ROYALTIES

1. General Considerations

Although NASA has been obtaining and licensing patents for employee inventions for many years, there has been increased Government-wide emphasis, buttressed by statutory enactments, on this activity in recent years. This increased emphasis has re-shaped the patent and licensing activities of NASA and all other Federal agencies in two significant ways. First, clear authority has been provided for all Federal agencies to grant exclusive or partially exclusive, royalty-bearing licenses. This authority was provided by Pub. L. 96-517, which amended Title 35 of the United States Code by adding new sections 207-209. The amendment assured the exclusivity necessary to attract risk capital to further develop and market licensed inventions initially developed in the Federal laboratories. Second, and more recently, has been the authority for Federal agencies to retain the royalty income received from the licensing of their inventions, and direction that at least 15 percent of such income be shared with the employee-inventor, with the remaining income to be used to support licensing and related technology transfer activities at the laboratory where the invention was made. This authority, and this direction, was provided in the Federal Technology Transfer Act of 1986 (Pub. L. 99-502, amending the Stevenson-Wydler Technology Innovation Act of 1980). The objective was to involve, positively, Federal employees in the technology transfer process, and to reward their successful efforts in being so involved. Taken together, these two significant changes are intended to transfer technology produced in the Federal laboratories to the private sector for commercial use through the exclusivity provided by patent licensing so as to benefit the national economy and enhance the international competitive posture of the United States.

2. Invention Evaluation and Patent Filings

The starting point in the process is the acquisition of patents on inventions that may be licensed. Thus, all NASA employees are required (by NMI 3450.2B) to report inventions made as part of their official duties, and to which NASA has the right to acquire title. In addition, NASA may acquire title to inventions made by contractors if title is not waived to, or acquired by, the contractor pursuant to either section 305(f) of the National Aeronautics and Space Act of 1958, as amended (42 U.S.C. 2457(f)) or 35 U.S.C. 200, et. seq, whichever is applicable.

All inventions so made and reported by a NASA employee or contractor are evaluated for their significance and patentability. During the evaluation process a determination is also made by Patent Counsel as to NASA's right to obtain title (ownership) to the invention and any patents that may be obtained thereon. This determination is made pursuant to criteria set forth in Executive Order 10096 for employee inventions; and pursuant to applicable contract provisions and regulations for contractor inventions. As a general rule, a

Federal agency has the right to acquire title to any invention that bears a direct relation to or was made in the performance of the official duties of an employee. If, however, an agency decides not to obtain a patent because of lack of interest in the invention, rights may be retained by the employee. For contractor inventions, the contractor is afforded first option to acquire title, and accordingly NASA acquires title to only those inventions for which the contractor has not exercised that option.

The evaluation of the invention includes a two-step process. First, the significance of the invention to NASA is evaluated from a programmatic point of view. Second, if the invention is considered significant to NASA, its patentability from a legal point of view is assessed.

As to significance, three factors are considered: the technological contribution the invention represents; the extent the invention may be used by NASA in its programs; and the commercial potential of the invention. If the evaluation is high in any of the three areas -- with commercial potential being the most important and the determinative factor if doubtful in the other two areas -- a decision is made to proceed to the next step of conducting a patentability search. This decision to proceed is qualitative and subjective, and is made by the Patent Counsel of the Field Center where the invention was made after obtaining input from cognizant technical personnel other than the inventor.

A patentability search includes a search of the "prior art," including the files of existing patents in the relevant fields of technology in the U.S. Patent and Trademark Office. The purpose is to determine whether the invention appears to meet the statutory standards of patentability, consisting of utility, novelty, and unobviousness. This determination is a professional one made by the Patent Counsel at the Field Center where the invention was made. If it appears that the standards of patentability can be met, based on a review of the prior art, the Patent Counsel proceeds with the preparation and filing of a patent application, and conducts the necessary prosecution of the patent application before the U.S. Patent and Trademark Office to completion -- usually by the issuance of a United States Patent.

3. Licensing Activities

Whenever NASA files for a patent, the invention is made available for licensing. A patent first and foremost provides its owner, or licensees of its owner, the right to exclude unauthorized (i.e. unlicensed) persons from making, using, or selling the patented invention. Thus, whenever a Federal agency exclusively licenses an invention for commercial use, only its licensee can make, use, or sell the invention in a commercial product line. The agency, of course, has the option to license an invention nonexclusively, but NASA has found that licensing with at least some degree of exclusivity is usually an additional incentive, and in some instances a necessity, in promoting commercialization. This is because commercialization of an invention will require a great deal of further development and marketing to bring the invention to the marketplace from its birthplace at a Federal laboratory. Also, for start-up companies, some degree of exclusivity is usually needed to attract venture capital for the commercialization effort. In any event, some exclusivity to protect the investment against second-to-market copiers, who would compete without having to recover the cost of commercialization, is often necessary for new products to be brought from the laboratory to the marketplace.

Thus, NASA has the flexibility to grant either an exclusive, partially exclusive, or non-exclusive license under any resulting patent, under the authority provided by 35 U.S.C. 207-209 (and NASA's Licensing Regulation, 14 CFR 1245.2) depending on the need for commercialization. The marketplace -- as determined by the interest in the invention by one or more responsible applicants -- usually establishes whether exclusive, partially exclusive, or nonexclusive licenses are needed to commercialize a given invention. Since NASA does not itself commercialize inventions, it also does not prejudge the need for exclusivity. However, all applicants for a license are required to provide plans and intentions as to how they are to achieve practical application (i.e. commercialization) of the invention. Also, any intent to grant other than a nonexclusive license must be published for notice and comment in the Federal Register. Both these requirements are set forth in 35 U.S.C. 209. If the plans to achieve practical application are satisfactory, and there is no substantive reason identified as the result of the notice and comment, the requested license will be granted based on specific terms and conditions that are negotiated.

The most common way to announce the availability of any NASA invention for licensing is by publication of an abstract in the NASA Tech Brief journal. Accompanying the abstract will be a statement as to whether or not a patent has been filed for, as well as who to contact to determine the exact patent and licensing status. NASA also publishes a complete catalog of all of its patents that may be available for licensing in the NASA Patent Abstracts Bibliography. In addition, and of increasing frequency under new Government-wide initiatives to make Federal laboratories more accessible to the private sector, there are more direct inquiries to the various NASA field centers having known expertise in certain areas of technology that may be commercialized.

Whenever an application for a license is received, it is forwarded to the Patent Counsel at the field center that has filed for and/or received the patent, for initial processing and a preliminary recommendation. This includes a check on the availability for licensing, a review of the applicant's requisite plans and intentions, and recommendations as to the license terms and conditions, including royalties. This will often include dialogue and possibly early negotiations with the prospective licensee. After the initial processing, the preliminary recommendations are then forwarded to NASA Headquarters for a final determination to grant, deny, or modify as may be required under established policies. At that time, any required notices will be published in the Federal Register. If the decision is to proceed with the license, including consideration of any comments as the result of a notice in the Federal Register, a final determination is made and the license agreement is negotiated by Headquarters in coordination with Field Center Patent Counsel.

4. Royalty Sharing

All NASA patent licenses require royalty payments or other consideration from the licensee. These royalties are distributed in part to the employee inventor and in part to the NASA Field Center where the invention was made, as required by 15 U.S.C. 3710c. This law, which has been in effect for little over two years, requires at least 15 percent of the royalty income to be distributed to the employee inventors. (Royalties are not shared, however, with employees of independent contractors.) The remaining royalties for employee inventions are distributed to the Field Center where the invention was made to support further licensing and technology transfer activities, including further rewards to Center employees engaged in such activities at the discretion of Center management. Royalties obtained from the licensing of contract inventions are forwarded to the U.S. Treasury.

The royalty-sharing requirements for employee inventions have been implemented by NASA through NMI 3450.2B (Appendix C). Under this NMI, NASA distributes all of the first $2,000 of royalties received under a license to the employee-inventors. In addition, each employee inventor normally receives 20 percent of any royalty income above the first $2,000. This distribution scheme is more liberal than the statutory minimum in that it is NASA's policy to place greater emphasis on rewarding innovative employees, encouraging their reporting of inventions, and seeking participation in efforts to achieve commercial use of the invention, than in offsetting program costs.

5. Summary of Activities for the Preceding Year

One emphasis during FY 1989 was to maintain its patent filing activities and pursue royalty-bearing licensing opportunities. The overall results for NASA laboratory inventions are:

Patent Acquisition

	NASA Employees	Contractors
--Inventions disclosures received:	256	960
--Patent applications filed:	80	70
--Patents issued:	55	72

Licensing

--Licenses granted:	6
--Royalties received:	84,338
--Royalties distributed to employees:	30,535
--Employees receiving royalties:	35
--Royalties for distribution to Field Centers	22,205
--Royalties to be returned to Treasury	1,450

More detailed statistics regarding these results, including laboratory-by-laboratory break-downs for FY 1981 through FY 1989, are provided in Appendix E.

Of note is the fact that the number of invention disclosures received has increased 10 percent over the previous three years, and patent filings have increased approximately 16 percent over the same period. While such an increase is welcome, it requires additional resources to process, evaluate for commercial potential, and make patentable novelty decisions prior to commencing the patent application preparation phase. Current resources available for patent filings are close to the saturation point, and therefore, future filings will have to be limited accordingly notwithstanding an increased number of invention disclosures. Thus one action initiated regarding the managing of the program was to explore, with some laboratories, the possibility of contracting for services outside of NASA for the preparation of patent applications.

Also of note is the fact that since the advent of the requirements for royalty sharing (pursuant to the Federal Technology Transfer Act of 1986), royalty-bearing exclusive licenses are assuming greater importance. Such licenses, however, cannot be granted pro forma, or by "boilerplate." They require a review of the plans and intentions of the applicant (35 U.S.C. 209(a)); and a publication of an intent to grant in the Federal Register and an analysis of and a determination made with respect to the comments received (35 U.S.C. 209(c) (1)). Finally, if these hurdles have been passed, substantial business-like negotiations with the prospective licensees are required. Several significant NASA inventions were subject to that process during FY 1989, diverting even more resources from the patent acquisition process. Thus, another action taken regarding the managing of the program was to encourage involvement of laboratory personnel, as early as possible, in the licensing process to focus on the most promising of inventions and the most responsible licensees.

Also during FY 1989, NASA became aware of several instances of allegations by an exclusive licensee that there was unlicensed (infringing) use of the exclusively licensed invention. Investigations have been initiated, and preliminary legal strategies developed, in those situations which warranted it. In one instance the patent in question has been submitted to a vigorous reexamination process to assure its validity in anticipation of bringing an infringement action. The Department of Justice has been briefed and contingent on the reexamination process a final decision will be made as to whether or not to institute a patent infringement suit. Actions of this type need to be pursued in order to maintain the creditability of the Government's patent licensing program.

Another action that was pursued during FY 1989 was in relation to a "priority" of invention dispute. The situation arose because the United States Patent and Trademark Office awarded claims in a patent application to another (foreign) party which dominated claims in a NASA improvement patent which was licensable and for which there was an interested licensee. NASA felt, and subsequent investigations seem to confirm, that NASA could obtain "priority" (i.e. establish an earlier date of invention) for such claims, as well as the claims NASA had been awarded in its own patent. Since the licensee was very reluctant to commercialize the NASA invention unless this matter was resolved, the Department of Justice, at NASA's request, instituted a suit in District Court (under 35 U.S.C. 146) to contest priority of invention for the dominant patent claims. During the discovery phase of this suit certain "prior art" was discovered that would seem to invalidate the dominant claims in issue (but not claims in NASA's improvement patent), thus making the NASA improvement patent readily licensable. Because of these factors, the Department of Justice is pursuing, at NASA's request, and prior to trial of the priority issue, the possibility of a settlement whereby the claim in issue would not be asserted against NASA or its licensees. If settlement is not reached, NASA and the Department of Justice are prepared to go to trial on the priority issue.
Finally, an effort was undertaken to review the entire

licensing docket, particularly those patents with multiple nonexclusive licenses, with the objective of terminating, those licenses where the invention either is not being commercialized or the licensee has abandoned attempts to do so. The objective is to assure that the patents are more readily available, possibly on a more exclusive basis, to those entities who are willing to pursue commercialization.

6. Plans for the Upcoming Year.

Top priority will be given to making investigations and developing, in coordination with the Department of Justice, actions to be taken regarding the allegations of unlicensed use (infringement) of NASA patents that have been exclusively licensed. An exclusive license can be considerably devalued if there is unlicensed use or infringement that is allowed to continue unabated. The ultimate viability of the Government's licensing and royalty sharing programs will depend on the Government's resolve to protect both its rights and the rights of its royalty-paying licensees through appropriate legal actions. A few precedent-setting cases of successful action could be invaluable in preventing unlicensed use.

In addition, efforts will be directed, within the limits of available resources, towards maintaining at least the current rate of patent application filings. A portfolio of strong, enforceable patents on licensable technology is the foundation on which a viable intellectual property rights program is built. The possibilities of contracting-out will be further explored to handle the increasing workload.

Efforts will also be undertaken to more actively engage the Field Center Patent/Intellectual Property Counsel, as well as the inventors and their line management, in the licensing process. One Field Center has prepared a presentation for that purpose, and its use will be encouraged for all Field Centers. However, more involvement in the licensing process will require trade-offs with efforts in securing more patents because of resource constraints.

Finally, efforts will be undertaken to make those patents having commercial promise but not yet licensed more readily known to United States Industry. One possibility being explored is a periodic patents and licensing article in the NASA Tech Briefs Journal.

II-3. COPYRIGHT ACTIVITIES

As has been indicated, works "authored" by Federal employees in the performance of their official duties are not copyrightable. Studies have been undertaken by the General Accounting Office, and Congressional hearings have been held, on the possibility of amending the copyright laws to enable copyright of certain "technologies" (as distinguished from "information") created by Federal employees. Computer software is one area of technology where such an approach appears viable. Cocommittently, there will be a need to consider amendments to the laws relating to the authority for licensing and royalty sharing. NASA has been involved in, and is supportive of, such initiatives. If as the result of these studies and hearings there is a possibility of such legislation proceeding, NASA will review its present intellectual property rights infrastructure with the objective of including the necessary policies and procedures for securing copyright protection and licensing, and make an assessment of the resources needed for implementation.

It is also pointed out that presently COSMIC distributes NASA-developed computer software, as described in Section I. This distribution is by sale or lease (a contractual arrangement) and not under an intellectual property (i.e. copyright) license. In some selected cases, however, we have been obtaining copyright assignments from contractors (including from Caltech for some computer software developed at JPL), and have been making such copyright available to COSMIC for licensing. Contingent on how this may work out, consideration will be given to licensing through COSMIC, with adequate arrangements to accommodate any royalty sharing authority that may be provided.

II-4. TRADE SECRETS & RELATED MATTERS

As a practical matter trade secret or equivalent type protection is not available for innovations of Federal employees at the Government laboratories on any extensive basis. The authority that presently exists is limited to cooperative research and development agreements entered into under the authority of Section 12 of the Stevenson-Wydler Technology Innovation Act of 1980. Protection across the board in a more meaningful manner will require significant legislation that should be pursued only after extensive analysis and a coordinate effort by research and development agencies and cognizant Congressional committees. NASA would be interested in pursuing, and becoming engaged in, such activities, but it is premature to provide any further comments, or include any plans, in this Report.

II-5. CLOSER COORDINATION WITH THE TECHNOLOGY TRANSFER FUNCTION

Another important aspect of the technology transfer function is greater use of agreements (both cooperative and reimbursable) directed towards facilitating access to the technology, resources, and expertise available at the NASA laboratories. While as has been indicated NASA enters into such agreements under the authority of sections 203(c) (5) and (6) of the National Aeronautics and Space Act of 1958, as amended (42 U.S.C. 2473(c) (5) and (6)) rather than Section 12 of the Stevenson-Wydler Technology Innovation Act of 1980, the purpose and result are the same. Situations have arisen where such agreements can, under appropriate circumstances, provide assistance to a licensee of a NASA patent (for an invention not made under the agreement) in bringing the invention to the point of practical application. Such agreements can be very beneficial in bridging the gap between inventions arising from mission activities and commercial needs. It is believed that with closer coordination with other organizational elements using Space Act agreements NASA's patented technology can be better integrated into the technology transfer process. Thus efforts will be undertaken in the upcoming year to seek greater synergism between other organizational elements involved in the technology transfer function and NASA intellectual property program.

APPENDIX A

TECHNOLOGY ACCESS
AND
INFORMATION DISSEMINATION

Appendix A-1

PUBLICATIONS ACTIVITY

NASA TECH BRIEFS
GROWTH IN READERSHIP

1984	1985	1986	1987	1988	1989	1990
75,000	98,900	127,000	141,000	151,000	169,000	189,000

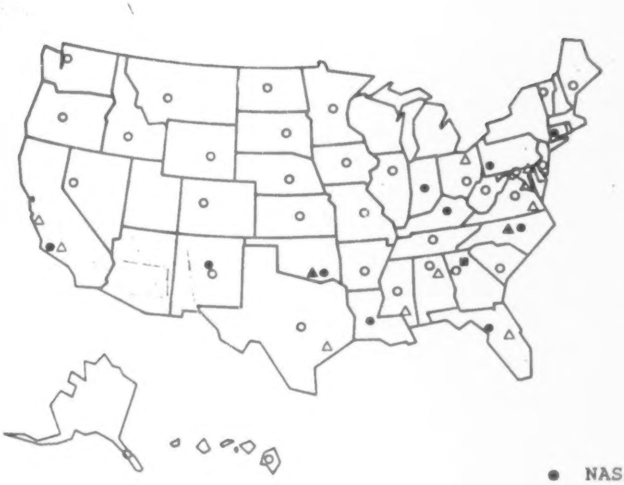
READERSHIP DISTRIBUTION

By Area of Primary Interest

Aerospace	26,072	Oceanography	237
Electronics	23,844	Industrial Equipment	18,201
Computers	14,049	Research Laboratories	10,151
Communications	12,256	Finance	175
Chemicals	4,139	Media	348
Materials	5,284	Packaged Goods	3,470
Power & Energy	5,648	Food/Agriculture	476
Biomedical	7,606	Education	5,404
Nuclear	609	Technical Consultant	7,687
Transportation	6,175	Libraries	197
Government	8,273	Other	13,265
Defense	11,978	Total.................	185,544

NASA's Technology Transfer System

Appendix A-2



△ ***Field Center Technology Utilization Officers:*** manage center participation in regional technology utilization activities.

● ***Industrial Applications Centers:*** information retrieval services and assistance in applying technical information relevant to user needs.

○ ***Industrial Applications Center Affiliates:*** state-sponsored business or technical assistance centers that provide access to NASA's technology transfer network.

■ ***The Computer Software Management and Information Center (COSMIC):*** offers government-developed computer programs adaptable to secondary use.

▲ ***Application Teams:*** assist agencies and private institutions in applying aerospace technology to solution of public problems.

● NASA IAC

o IAC Affiliate

o Alabama

Johnson Research Center
University of Alabama-Huntsville
Huntsville, Alabama

o Alaska

Alaska Economic Development Center
University of Alaska at Juneau
Juneau, Alaska

o Arkansas

Industrial Research and Extension Center
University of Arkansas
Little Rock, Arkansas

Arkansas Center for Technology Transfer
University of Arkansas
Fayettevelle, Arkansas

Arkansas Science and Technology Authority
Little Rock, Arkansas

- California

  NASA Industrial Applications Center
  University of Southern California
  Los Angeles, California

○ Colorado

  Business Advancement Center
  University of Colorado-Boulder
  Boulder, Colorado

- Connecticut

  NERAC, Incorporated
  Tolland, Connecticut

- Florida

  Southern Technology Applications Center
  University of Florida
  Gainsville, Florida

○ Georgia

  Economic Development Laboratory
  Georgia Institute of Technology
    Research Institute
  Atlanta, Georgia

○ Hawaii

  Pacific Business Center Program
  University of Hawaii
  Honolulu, Hawaii

○ Idaho

  Idaho Business Development Center
  Boise State University
  Boise, Idaho

○ Illinois

  Argonne National Laboratory
  Argonne, Illinois

- Indiana

  Aerospace Research Applications Center
  Indianapolis Center for
    Advanced Research
  Indianapolis, Indiana

- Iowa

  CIRAS - Iowa State University
  Ames, Iowa

- Kansas

  Kansas Technology Enterprise Corporation
  Topeka, Kansas

● Kentucky

  NASA/UK Technology Applications Program
  University of Kentucky
  Lexington, Kentucky

● Louisiana

  NASA/SU Industrial Applications Center
  Southern University
  Baton Rouge, Louisiana

- Maine

  Production Technology Center
  University of Southern Maine
  Gorham, Maine

- Maryland

  Technology Extension Service
  Engineering Research Center
  University of Maryland
  College Park, Maryland

- Minnesota

  Governor's Office of Science
  and Technology
  St. Paul, Minnesota

- Mississippi

  Mississippi Technology Transfer Office
  Stennis Space Center, Mississippi

- Missouri

  Technology Search Program
  University of Missouri-Rolla
  Rolla, Missouri

o Montana

University Technical Assistance Program
College of Engineering
Montana State University
Bozeman, Montana

o Nebraska

Nebraska Technical Assistance Center
University of Nebraska
Lincoln, Nebraska

o Nevada

Desert Research Institute
Reno, Nevada

o New Jersey

Southern New Jersey Technology Consortium
Pleasantville, New Jersey

• New Mexico

Technology Applications Center
University of New Mexico
Albuquerque, New Mexico

• North Carolina

NASA Industrial Applications Center
North Carolina Science and Technology
Research Center
Research Triangle, North Carolina

o North Dakota

Technical Services Center for Innovation
and Business Development
Grand Fork, North Dakota

o Ohio

Ohio Technology Transfer Organization
Columbus, Ohio

• Oklahoma

NASA Central Industrial Applications Center
Durant, Oklahoma

○ Oregon

Regional Services Institute
Eastern Oregon State College
La Grande, Oregon

● Pennsylvania

NASA Industrial Applications Center
University of Pittsburgh
Pittsburgh, Pennsylvania

○ South Carolina

The State Board for Technical and
Comprehensive Education
Columbia, South Carolina

○ South Dakota

College of Engineering
South Dakota State University
Brookings, South Dakota

○ Tennessee

Center for Industrial Services
University of Tennessee
Nashville, Tennessee

○ Texas

Technology Business Development
Texas Engineering Experiment Station
College Station, Texas

○ Vermont

Agency of Development and
Community Affairs
State of Vermont
Montpelier, Vermont

○ Virginia

Center for Innovative Technology
Herndon, Virginia

○ Washington

Small Business Development Center
Washington State University
Pullman, Washington

- West Virginia

  Science and Technology Center
  Charleston, West Virginia

- Wyoming

  Institute of Business Management Services
  College of Commerce and Industry
  University of Wyoming
  Laramie, Wyoming

NASA has been designated as lead Agency to develop the following Center (FY 1990-1995) in support of the nationwide infrastructure for Federal technology transfer:

National Technology Transfer Center (NTTC)
Wheeling Jesuit College
Wheeling, West Virginia

Appendix A-3

INDUSTRIAL APPLICATION CENTER (IAC)

EXAMPLES OF NETWORK ACHIEVEMENTS

Cited below are accomplishments and benefits achieved over the past year derived from services and support that led (or will lead) towards a commercial product, process, or improvement:

Geographic Data (Spatial and Spectral)

A NASA Industrial Applications Center (NIAC) was successful in conducting remote sensing searches and retrieval in a variety of formats including Gemini, Apollo, Skylab, Apollo-Soyuz, Additionally, the Geographic Data Services (a senior activity) searches and retrieves NASA-generated aircraft scanner data, commercially acquired aerial photography, EOSAT, SICORP, NOAA, and other government and commercial data sets and published maps.

All of the above-mentioned forms of data are used by NIAC clients in the generation of their new products and services, primarily those described as the value-added earth observing industry and end-user communities. The benefits of these support services consist in providing a "one-stop shopping" mechanism for public inquiry regarding the types and availability of satellite images. Images attained from the NIAC have benefitted clients financially. For example, in a civil engineering project which involved determining the best location for bridge construction, the NIAC provided the imagery which allowed the client to establish the best location for the bridge. This discovery saved the company a significant amount of dollars.

Aluminum Products

A NASA Industrial Application Center (NIAC) client who develops and markets aluminum products for home building, automotive vehicles, and communications, was able to interpret, with the NIAC's assistance, climatic forces and window-screen weaknesses that contribute to structural damage of window frames.

The beneficial result was the invention and development of a "fail safe" screen pop-out system that protects the structural elements of screened enclosures used in hurricane-prone areas.

Gas Separation Technology

A NASA Industrial Applications Center (NIAC) applications analysis team was successful in identifying a number of unique applications and enhancements for a new gas separation technology that will result in both product improvement and increased sales for a Fortune 500 Company. A novel manufacturing process allows the size of pores in the fibers to be closely and uniformly regulated.

Invisible Braces

A joint effort between industry and a NASA Industrial Applications Center (NIAC) resulted in the successful development of "invisible" ceramic orthodonic braces. The information search and retrieval services provided by the NIAC to industry clients allowed industry clients to apply the information towards developing a material known as translucent polycrystalline alumina, or TPA, which is a major component used in manufacturing the braces.

Appendix A-4

TECHNOLOGY DISSEMINATION

CONFERENCES/SEMINARS/TRADE SHOWS FOR INDUSTRY IN 1989

The following list is a summary of the activities initiated and conducted by the NASA Field Centers TUOs/TU Contractors to facilitate and enhance public awareness of the Technology Utilization/Technology Transfer Program:

- Materials Technology Transfer Conference
- American Society of Cell Biology
- Industrial Expo '89'
- INPEX 4
- Tech Ohio
- Solid Waste Management Conference
- Tech Transfer Workshop for Louisianna Industrial Development Executives Association (LIDEA)
- Tech Transfer Workshop for Mississippi Industrial Coordinators
- Furniture Manufacturers Workshop (for furniture industry in Mississippi)
- Space Technology Small Business Conference
- Florida Industrial Resources Institute
- Federal Lab Consortium (regional mtgs. in Atlanta and Denver)
- Financial News Network
- Seminar for National Institute of Correction and California Institute of Corrections
- SAE Aerotech Exhibition and Conference
- NBC News - Burbank, CA
- Tech Commercialization Office sponsored: Seminar on Fiber Optics Rotation Sensors; Technology Information Mtg. (on Microelectronics); 15 day long seminars for specific industrial firms
- AIAA Aerotech 90
- Briefed Channel 2 (Nashville) on Tech Transfer Program
- Tennessee Valley Authority
- Mechanical Engineers Association
- Mississippi Tech Transfer Workshop
- Technical and Business Exhibition Symposium
- Conference on Independent Living
- SBIR Program and Materials Technology
- Kiwanis Space Technology Applications Show
- Florida Hi-Tech Counsel
- Florida Space Conference
- US Navy Best Mfg. Practices
- INVENTECH
- Space Technology Day
- High Tech Small Business Development Conference
- Federal High Tech '90'

FIELD CENTER STATE AGREEMENTS

0 MOU's executed for Adult Literacy, and Intelligent Tutoring System (JSC)
0 Sverdrup, Inc (contract engineer)
0 CORTEZ, Inc. (contract agreement)
0 Cleveland Advanced Mfg. Program - Great Lakes Area
0 MOU - Ames and IBM (non-proprietary technical exchange parallel processing computational fluid dynamics)
0 SSC and MSFC with States of Louisianna and Mississippi (tech transfer activities)
0 Lockheed (contractor support)
0 MOU with the states of Alabama, West Virginia, Tennessee, Georgia, Louisianna, Mississippi (cooperative effort to tranfer NASA derived technology to the private sector
0 MSFC contracts with Vanderbilt U. (Robotics), Univ. of Georgia and Oglevee Nursery (Farms), Princeton Univ. (plasma/oxygen), Oklahoma University (part tolerance in complex systems)
0 MOU between LaRC and the States of Virginia, Maryland and West Virginia (to provide assistance to industry with NASA technical expertise
0 MOU between KSC and the State of Florida
0 MOU between KSC and the American Cancer Society of Florida
0 MOU between KSC and Walt Disney World

SERVICES AND SUPPORT LEADING TO A COMMERCIAL PRODUCT

0 Space Science Class Materials - provided space course outlines and lesson plans to be utilized throughout US school systems;

0 Lightening Detection Project - agreement with Channel 48 to access Marshall's Advanced Lightening location detection system;

0 Hot Lunchbox Meals - container packaging for hot lunchbox meals;

0 Education Enhancement - Project LASER (a mobile NASA Teacher Resource Center)

0 Ultrasound Burn Depth Monitor - first marketable system to be available for tests in May 1990

APPENDIX B

TECHNOLOGY APPLICATIONS

Appendix B-1

CURRENT APPLICATIONS ENGINEERING PROJECTS

Biomedical

Virtual Image Helmet for the Visually Impaired
Computational Fluid Dynamic Heart Flow
Ingestible Temperature Monitoring System
Glaucoma Detection
Coronary Artery Bypass Flow
Binaural Hearing Aid
Functional Electrical Stimulator for Muscles
Cerebral Fluid Shunt
Low Vision Image Enhancement System
Malignant Melanoma Detection
Automated Digital Microscopy Chromosomes
Flow Cytometry for Body Cell Diagnostics
Virtual Environment Medical Education
Monoclonal Antibodies Cancer Diagnostics
Enhanced Cancer Diagnostics with Magnetic Resonance Imaging
Digital Hearing Aid
Computer Aided Design for Orthopedic Shoes
Diagnosis of Decubitus Ulcers (Bed Sores)
Hyperthermia Monitoring System
Intercranial Pressure Measurement
Fetal Heart Monitor
Ultrasound Dosage Measurement
Pulmonary Muscle Measurement
High Strength Spinal Screw Materials
Orthopedic Joint Implants
Emergency Vehicle Alert System

Education

Artificial Intelligence for Adult Literacy
Intelligent Tutoring Systems for Teaching Physics

Environment

Crop Growth Research Chamber
Image Visibility Modeling of Air Pollution
Heat Pipe Thermal Storage Furnace
Automated Citrus Tree Classification
Heat Pipe Radon Removal
Plant Root Growth System

Industrial

Electroluminescent Flat Panel Display
Oscillating Cascade System for Energy Production
Semiconductor Etching Technique

Appendix B-2

APPLICATIONS ENGINEERING

EXAMPLES OF PROJECT ACHIEVEMENTS

Decribed below are two projects which illustrate achievements made during the past year in the application of NASA-developed technology to significant problemys in the public sector:

Excimer Lasers

Each year, over 250,000 people in the U.S. undergo balloon angioplasty to clear blocked coronary arteries. This technique, however, merely compresses the plaque against the artery walls and normally leads to a repeat procedure inmore than one-third of the patients. Continued degradation even leads to open heart surgery in some cases.

Surgeons at Cedar Sinai Hospital in Los Angeles are now using an excimer laser system, developed by the Jet Propulsion Laboratory (JPL) for space applications, to vaporize arterial plaque without excess heat which could damage vessel walls. The laser is controlled precisely through a magnetic switching element, also developed at JPL. Following initial clinical success, a new company, Advanced Interventional Systems, Inc., was founded to commercialize the excimer laser for routine surgical use. Excimer laser angioplasty has been tested extensively in peripheral arteries with the first coronary application performed in early 1989.

Burn Depth Measurement

Of the two million Americans who suffer serious burns each year, 70,000 receive intensive care -- and in some 10 to 12,000 cases, the burns are often fatal. The primary cause of death is bacterial infection, frequently exacerbated by long periods spent waiting for spontaneous sloughing of necrotic tissue. Burn surgeons have stated the need for improved methods to accurately determine the depth of tissue which must be removed to promote more rapid healing and minimize possible infection of the burn area.

NASA Langley Research Center scientists have devloped a high-frequency ultrasound instrument capable of 0.1 mm resolution to detect the interface between viable and non-viable tissue in the burn site. Clinical tests conducted at the Medical College of Virginia last year, have been quite promising. In 1989, NASA licensed the technology to a small business firm, Fulmer Dyson, Inc., to commercialize the burn depth measurement instrument.

APPENDIX C

NASA MANAGEMENT INSTRUCTION 3450.2B

INVENTIONS MADE BY EMPLOYEES UNDER NASA ADMINISTRATIVE JURISDICTION

APPENDIX C

NASA
Management
Instruction

NMI 3450.2B
Effective Date October 13, 1987
Expiration Date October 13, 1992

Responsible Office: G/General Counsel

Subject: INVENTIONS MADE BY EMPLOYEES UNDER NASA ADMINISTRATIVE JURISDICTION

1. PURPOSE

This Instruction sets forth the policies, procedures, and responsibilities for the reporting of, and the determination of rights to, inventions made by Government employees under the administrative jurisdiction of NASA; the filing for, obtaining, and maintaining patents on such inventions; the referral of such inventions to the NASA Inventions and Contributions Board (ICB) for a monetary award; and the distribution of royalties or other income received from the licensing of such inventions.

2. APPLICABILITY AND SCOPE

This Instruction is applicable to NASA Headquarters and field installations. It applies to any invention made by a NASA employee or an employee of another Government agency who is under the administrative jurisdiction of NASA.

3. AUTHORITY

a. Sections 102(c)(5), 203(a)(3), and 305(h) of the National Aeronautics and Space Act of 1958, as amended (42 U.S.C. 2451, *et seq*.).

b. Sections 13, 14, and 15 of the Stevenson-Wydler Technology Innovation Act of 1980, as amended by Pub. L. 99-502 (15 U.S.C. 3701, *et seq*.).

c. Executive Order 10096 and Title 37 of the Code of Federal Regulations (CFR), Part 100.

d. Executive Order 12591.

4. RELATED INSTRUCTIONS

a. NMI 5109.3, "Licensing of NASA Inventions."

b. NMI 5700.3, "Awards for Reported Scientific and Technical Contributions - NASA and Contractor Employees."

5. POLICY

It is NASA policy to:

a. Protect the Government's interest in, and to provide for the widest practicable and appropriate dissemination, early utilization, expeditious commercial development, and continued availability of, inventions made by employees under the administrative jurisdiction of NASA.

b. Be fair and impartial in the administration of the rights to such inventions, and to afford an employee-inventor the opportunity to retain rights to inventions for which there is insufficient Government interest or equity for NASA to acquire title.

c. Assure that all employees making and reporting inventions on which NASA files patent applications are considered by the ICB for an initial monetary award as well as a supplemental monetary award, based both on the commercial application of the invention and its contribution to NASA's missions and program objectives.

d. Pay to the employee-inventors a percentage of any royalties and other income received from the licensing of NASA-owned inventions, and to make the remainder of the royalties or other income available to the field installation where the inventions shall be made to be used for activities directed to increasing the licensing potential of NASA-owned inventions, or available to the ICB for awards for contributions by that field installation.

6. RESPONSIBILITIES

a. Employees. Employees under the administrative jurisdiction of NASA are responsible for:

(1) Assuring that inventions are reported in accordance with paragraph 7.

(2) Informing the Installation Patent or Intellectual Property Counsel of any proposed publications, public use, or oral public disclosures which may bar patent protection (domestic or foreign), and taking all reasonable steps to prevent such bars.

(3) Agreeing upon request to assign the invention to the Government; or, if it is believed that NASA is not entitled to an assignment, furnishing sufficient information regarding the circumstances under which the invention was made and the relationship of the invention to the employee's official or assigned duties so that a determination of rights can be made pursuant to paragraph 8.

(4) Executing all necessary documents for NASA to file and prosecute patent applications and to obtain and maintain patents on any invention for which the Government obtains assignment of title and NASA decides to protect by patenting in any country.

(5) Assisting, as requested, in the prosecution of the patent application, and making available records relating to the conception or reduction to practice of the invention if needed to establish inventorship or priority of invention.

(6) Complying with NHB 1900.1, "Standards of Conduct for NASA Employees," in participating with NASA licensees in efforts to commercialize NASA-owned inventions.

b. Employee's Supervisors and Other Technical Personnel. The supervisor of the employee-inventor, and other NASA personnel having immediate technical cognizance of the invention, are responsible for providing on request:

(1) Either concurrence with, or additional comments on, any information regarding the circumstances under which the invention was made (as provided by the employee-inventor under paragraph 7b(2)).

(2) An evaluation of the technical significance of the invention, and to the extent feasible, an assessment of the commercial potential of the invention.

c. Office of General Counsel. The General Counsel, and by delegation to the Associate General Counsel (Intellectual Property) and Installation Patent or Intellectual Property Counsel, is responsible for:

(1) Making the NASA determination of the respective rights of the Government and the employee-inventor in any reported invention, and advising the employee in a timely manner of that determination.

(2) Designating a liaison officer to deal with the Commissioner of the Patent and Trademark Office with respect to any rights determination matters under E.O. 10096 and 37 CFR Part 100.

(3) Determining whether there is sufficient interest to obtain patent protection (domestic or foreign) on any invention reported to NASA for which the Government has the right to obtain either title or a Government license, and based on such determination either:

(a) Authorize the filing of a patent application by NASA and so notify the employee-inventor.

(b) Notify the employee-inventor of the insufficient Government interest in pursuing patent protection and allow the employee-inventor the opportunity to do so.

(4) Notifying the ICB of any NASA authorization to file a patent application on any invention made and reported by an employee under the administrative jurisdiction of NASA.

(5) Taking all suitable and necessary steps to obtain and maintain patent protection (domestic and foreign) on any reported invention to which the Government has the right to obtain either title or a Government license and for which there is sufficient Government interest to do so.

(6) Ensuring that all inventors named in a patent application meet the requirements of inventorship under law.

(7) Promoting the licensing for commercial use of all NASA-owned inventions for which patent applications have been filed or patents obtained (either domestic or foreign).

(8) Assuring that all royalties and other income received from a licensed patent application or patent are forwarded, along with the designation of the field installation where the invention was made and the identity of the inventor or coinventors entitled to receive royalty payments, to the Financial Management Division, Office of the NASA Comptroller, for distribution in accordance with paragraph 11.

(9) Notifying the Field Installation Directors of the amount of royalties and other income available for distribution to their field installations or the ICB after the end of each fiscal year received, and informing the Director, Financial Management Division, of the election by the Directors of the Field Installations of the transfers to be made.

d. Director, Financial Management Division. The Director, Financial Management Division, Office of the NASA Comptroller, is responsible for establishing and maintaining a system for the accounting and distribution of royalties and other income to employee-inventors, to the field installation where the invention was made, or to the ICB, in accordance with paragraph 11.

e. Field Installation Directors. Field Installation Directors are responsible for ensuring that all royalties and other income available for distribution to their field installations are used and obligated in accordance with paragraph 11c.

7. REPORTING OF INVENTIONS

a. Each employee is required to submit to the Office of General Counsel, or to the delegated Field Installation Patent or Intellectual Property Counsel, a disclosure of each invention made by the employee while under the administrative jurisdiction of NASA (RCS 10-0000-00319).

b. With respect to any invention reported pursuant to subparagraph a, the employee-inventor shall either:

(1) Agree to assign title of the invention to the Government, in any country, upon request of NASA.

(2) If the employee-inventor believes NASA is not entitled to such assignment of the invention, the employee-inventor is to provide the requested information regarding the circumstances under which the invention was made and the relationship of the invention to the employee's official or assigned duties so that a rights determination can be made pursuant to paragraph 8.

c. Employees are cautioned that a premature publication disclosing the invention, public use of the invention, or an oral public disclosure of the invention, may preclude the invention from being patented. Under United States law a patent may not be obtained unless a patent application is filed within 1 year from the date of a publication disclosing the invention, or within 1 year from the first public use of the invention. In many foreign countries a patent application must be filed prior to any publication date or any public use, and even prior to any oral public disclosure of the invention. In order to avoid such bars to patent protection, and the possible loss of royalty income, inventions should be disclosed to Installation Patent or Intellectual Property Counsel in sufficient time prior to any proposed publication, public use, or oral public disclosure, for evaluation and processing in accordance with paragraph 9, and for patent applications to be filed. Employees should also, after such disclosure, advise the Field Installation Patent or Intellectual Property Counsel of any proposed publications or other activities disclosing the invention.

8. DETERMINATION OF RIGHTS TO EMPLOYEE INVENTIONS

a. A determination of the respective rights of the Government and of the employee-inventor in and to any invention made by a Government employee while under the administrative jurisdiction of NASA will be made in accordance with the criteria set forth in Executive Order 10096 (also set forth in 37 CFR Part 100). In accordance therewith, and except as provided by subparagraph b or c, NASA may require assignment of title in and to any such inventions which:

(1) Were made during working hours.

(2) Were made with a contribution by the Government of facilities, equipment, materials, funds or information, or the time or services of other Government employees on official duty.

(3) Bear a direct relation to or were made in consequence of the official duties of the employee.

b. If an invention made by an employee does not bear a direct relation to, or was not made in consequence of, the official duties of the employee, but otherwise was made during working hours, or with a contribution by the Government of facilities, equipment, materials, funds or information, or of time or services of other Government employees on official duty, NASA may, if such contributions are insufficient equitably under the criteria set forth in E.O. 10096 to require assignment to the Government, leave title with the employee, subject to the reservation to the Government of a nonexclusive, nontransferable, irrevocable, paid-up license to practice the invention or have the invention practiced throughout the world by or on behalf of the Government.

c. If none of the circumstances set forth in subparagraphs a(1)-(3) exist, the employee-inventor may retain all rights, title, and interest in the invention.

d. As to any invention for which the Government has the right to request assignment of title in accordance with subparagraphs ~~a(1)-(3)~~, if upon evaluation pursuant to paragraph 9 NASA determines (at any time prior to the filing of a patent application) that there is insufficient Government interest to pursue and obtain patent protection on the invention, the employee-inventor will be promptly notified and given the opportunity to retain title, subject to the reservation to the Government of the same license as set forth in subparagraph b. The inventor's right to retain title may also be conditioned on the timely filing of a patent application by the employee-inventor when NASA determines that the Government has or may have a need to practice the invention. In addition, as to any invention for which NASA has filed a domestic patent application, if NASA does not take action to cause a patent application to be filed in a particular foreign country either (1) within 8 months of such domestic filing, or (2) within 6 months of declassification of an invention previously under secrecy order, whichever is later, the employee may retain title in that country, subject to a nonexclusive, irrevocable, royalty-free license to the Government in any patent that may issue thereon, including the right to issue sublicenses for use on behalf of the Government in furtherance of the policies of the Government.

9. EVALUATION AND PROCESSING OF INVENTIONS

Any reported invention for which the Government has the right to obtain either title or a Government license will be evaluated for Government interest, including both anticipated Government use and commercial potential; and if such interest exists, for patentability. Based on such evaluations, NASA will determine whether or not to pursue patent protection (domestic and foreign) thereon, and will inform the employee-inventor. If NASA obtains assignment of title and files a patent application on the invention in any country, the patent application and any patent issuing thereon will be made available for licensing in accordance with NMI 5109.3. Any royalties or other income received from such licensing will be distributed in accordance with paragraph 11.

10. AWARDS FOR INVENTIONS

All inventions made by employees under the administrative jurisdiction of NASA and reported to NASA will be considered for a monetary award under Section 306 of the National Aeronautics and Space Act of 1958, as amended, by the ICB in accordance with the policies and procedures set forth in NMI 5700.3. An initial minimum cash award will be recommended by the ICB based on the authorization to file a patent application. In addition, the ICB may recommend a supplemental monetary award in an amount that will be based on the evaluation of the technical and commercial merits of the invention. The ICB will also consider awards for scientific and technical contributions not subject to patent applications in accordance with NMI 5700.3. NASA may also grant awards for superior accomplishments and for cost savings that may result from an invention under the Incentive Awards Act, 5 U.S.C. 4501-4514, in accordance with NMI 3451.1, "NASA Incentive Awards Program."

11. DISTRIBUTION OF ROYALTIES

a. Whenever NASA licenses for commercial use one or more inventions covered by one or more patents or patent applications, any royalties or other income received from such licensing shall be distributed to employee-inventors in accordance with subparagraph b, and to the field installations or the ICB in accordance with subparagraph c.

b. Distribution to the employee-inventors will be as follows:

(1) For the first $2,000 accumulated each fiscal year under each license:

(a) Where the patents and/or patent applications included in a license name the same sole employee-inventor, that employee-inventor shall receive the first $2,000 of the royalties or other income accumulated under such license.

(b) Where the patents and/or patent applications included in a license name the same employee-coinventors, the first $2,000 of the royalties or other income accumulated under such license will be distributed to the employee-coinventors on an equal share basis.

(c) Where the patents and/or patent applications included in a license name different employee-inventors, or different employee-coinventors, the first $2,000 of the royalties or other income accumulated under such license will be distributed on an equal share basis.

(d) Where two or more of the patents and/or patent applications included in a license name the same employee-inventor, or the same employee-coinventors, and other employee-inventors are also named, the first $2,000 of royalties or other income accumulated under such license will be distributed on an equal share basis, with the number of shares equalling the number of employee-inventors for the patents or patent applications included in a license. Any inventor or coinventor named more than once will receive a number of shares which equals the number of times named on the patents or patent applications included in the license.

(2) Each of the employee-inventors or coinventors named on patents and/or patent applications included in a license will also receive a minimum of 20 percent of the royalties or other income in excess of the first $2,000 accumulated each fiscal year under each license. When the number of inventors/coinventors exceeds five, the amount in excess of the first $2,000 will be distributed on an equal share basis. Any inventors or coinventors named more than once will receive a 20 percent distribution or share for each time named on patents or patent applications included in a license.

(3) The distribution will be made to each employee-inventor named as an inventor or coinventor on any patent or patent application licensed under NMI 5109.3. Royalties and other income received during the fiscal year (October 1 - September 30) will be distributed no later than December 10 following the end of the fiscal year received. Distributions may be made to each employee-inventor at any time during the calendar year when the amount calculated for distribution exceeds $1,000 per employee/inventor or when administratively expedient. Distributions will continue irrespective of any change in employment status of the employee. The distributions of royalties or other income to any one employee-inventor shall not exceed $100,000 per year, unless the President approves a larger amount (with the excess over $100,000 being treated as a Presidential Award under section 4504 of title 5, United States Code). Monies remaining after distribution under this

subparagraph shall be distributed in accordance with subparagraph c.

c. The Directors of the Field Installations where any licensed inventions were made will be notified by the Office of General Counsel of the balance of any royalties or other income that will, after payment to the employee-inventors under subparagraph b and subject to the limitation of subparagraph d, be made available for distribution to the field installations. The Directors of the Field Installations will advise the Office of General Counsel to distribute the remaining funds to their installation as R&D funds and/or to the ICB for the purpose of awards.

(1) Royalties and other income transferred to the field installations as R&D funds are to be used for the purpose of funding any activities (other than patent preparation, acquisition, or maintenance costs and fees) directed to increasing the licensing potential of any invention or class of inventions occurring at the field installation. Such activities may include (but need not be limited to) conducting market surveys to identify potential licensees and their needs; constructing models or prototypes of inventions for evaluation, testing, or demonstration purposes; educational and training activities directed to increasing employee and public awareness of the licensing potential for transferring NASA technology; and other related activities incidental to the administration and licensing of NASA inventions by the field installations or by NASA Headquarters.

(2) Royalties transferred to the ICB are to be used for the purpose of awards for contributions of employees of the field installation that transferred funds to the ICB.

(3) Transfer of royalties or other income to either a field installation or the ICB will be made no later than December 31 following the end of the fiscal year they were received by NASA. The royalties or other income so transferred must be used or obligated by the field installation or the ICB prior to the end of the fiscal year succeeding the fiscal year received by NASA.

Royalties or other income not used or obligated within that period will be transferred into the Treasury of the United States.

d. If, after payment to inventors under subparagraph b, the royalties or other income received by NASA in any fiscal year exceeds 5 percent of the budget of the field installation where the licensed inventions producing such royalties or other income are made, 75 percent of such excess will be paid to the Treasury of the United States by NASA and the remaining 25 percent shall be available for use and obligation in accordance with subparagraph b.

12. APPEALS AND PETITIONS BY EMPLOYEES

a. Any employee who has been aggrieved by a determination of rights by NASA pursuant to E.O. 10096 and 37 CFR Part 100 may obtain a review by the Commissioner of the Patent and Trademark Office of that determination by filing within 30 days (or such longer period as the Commissioner may for good cause shown in writing, fix in any case) after receiving notice of such determination, two copies of an appeal with the Commissioner. The Commissioner will forward one copy of such appeal to NASA. Upon receipt, NASA will furnish a report to both the Commissioner and the employee containing the information required by 37 CFR 100.7(b). The employee may also, within the times set in 37 CFR 100.7(b), file a reply to NASA's report, and will be afforded an opportunity for oral hearing if requested. The Commissioner's decision, based on the agency report, the employee's reply, as well as any facts developed at any hearing requested or additional facts the Commissioner may request, will be the final administrative determination of the matter.

b. Whenever NASA determines, with the employee's acquiescence, that title to an invention should be left with the employee (with or without a license to the Government), a report of that determination will be submitted to the Commissioner for review and final decision as required by 37 CFR Part 100. In the event that the Commissioner modifies that determination in a manner less favorable to the employee, the employee may petition the Commissioner for reconsideration under procedures set forth in 37 CFR 100.6(b)(3).

c. Any other determination made by NASA regarding patent application authorization, preparation, inventorship, filing and prosecution, the maintenance of any issued patent, or the licensing thereof, including the terms and conditions of the license, of any patent application or any patent issuing thereon, for any invention to which NASA has acquired rights under E.O. 10096 and 37 CFR Part 100, shall be at the sole discretion of NASA and is not appealable by the employee-inventor. Neither NASA nor any of its employees shall be liable to any party for any royalties not received or not collected under any license agreement for a NASA-owned invention.

13. CANCELLATION

NMI 3450.2A, dated July 7, 1986.

James C. Fletcher
Administrator

DISTRIBUTION:
SDL 1

APPENDIX D

NASA MANAGEMENT INSTRUCTION 5109.3B

LICENSING OF NASA INVENTIONS

APPENDIX D

NASA
Management
Instruction

NMI 5109.3B
Date November 2, 1981

Responsible Office: GP/Office of Assistant General Counsel for Patent Matters

Subject: LICENSING OF NASA INVENTIONS

1. INCORPORATION

   "Licensing of NASA Inventions" (14 CFR Part 1245, Subpart 2) is set forth in Attachment A and is hereby incorporated in the NASA Directives System.

2. CANCELLATION

   NMI 5109.3A, dated April 1, 1972.

Hans Mark
Deputy Administrator

Administrator

ATTACHMENT:
A: Licensing of NASA Inventions.

DISTRIBUTION:
SDL-1

Published in the Federal Register under Title 14, Chapter V, Part 1245, Subpart 2 (46 F.R. 54328-54331, November 2, 1981)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

14 CFR Part 1245

Licensing of NASA Inventions

AGENCY: National Aeronautics and Space Administration.

ACTION: Interim regulation with comments requested.

SUMMARY: The National Aeronautics and Space Administration (NASA) is revising its patent licensing regulations to conform with Pub. L. 96-517. This interim regulation provides policies and procedures applicable to the licensing of federally owned inventions in the custody of the National Aeronautics and Space Administration, and implements Pub. L. 96-517. The object of this subpart is to use the patent system to promote the utilization of inventions arising from NASA supported research and development.

EFFECTIVE DATE: July 1, 1981. Comments must be received in writing by December 2, 1981. Unless a notice is published in the **Federal Register** after the comment period indicating changes to be made, this interim regulation shall become a final regulation.

ADDRESS: Mr. John G. Mannix, Director of Patent Licensing, GP-4, NASA, Washington, D.C. 20546.

FOR FURTHER INFORMATION CONTACT: Mr. John G. Mannix, (202) 755-3954.

SUPPLEMENTARY INFORMATION:

PART 1245—PATENTS AND OTHER INTELLECTUAL PROPERTY RIGHTS

Subpart 2 of Part 1245 is revised to read as follows:

* * * * *

Subpart 2—Licensing of NASA Inventions

Sec.
1245.200 Scope of subpart.
1245.201 Policy and objective.
1245.202 Definitions.
1245.203 Authority to grant licenses.

Restrictions and Conditions

1245.204 All licenses granted under this subpart.

Types of Licenses

1245.205 Nonexclusive licenses.
1245.206 Exclusive and partially exclusive licenses.

Procedures

1245.207 Application for a license.
1245.208 Processing applications.
1245.209 Notice to Attorney General.
1245.210 Modification and termination of licenses.
1245.211 Appeals.
1245.212 Protection and administration of inventions.
1245.213 Transfer of custody.
1245.214 Confidentiality of information

Authority: 35 U.S.C. Section 207 and 208, 94 Stat. 3023 and 3024.

* * * * *

Subpart 2—Licensing of NASA Inventions

§ 1245.200 Scope of subpart.

This subpart prescribes the terms, conditions, and procedures upon which a NASA invention may be licensed. It does not affect licenses which (a) were in effect prior to July 1, 1981; (b) may exist at the time of the Government's acquisition of title to the invention, including those resulting from the allocation of rights to inventions made under Government research and development contracts; (c) are the result of an authorized exchange of rights in the settlement of patent disputes; or (d) are otherwise authorized by law or treaty.

§ 1245.201 Policy and objective.

It is the policy and objective of this subpart to use the patent system to promote the utilization of inventions arising from NASA supported research and development.

§ 1245.202 Definitions.

(a) "Federally owned invention" means an invention, plant, or design which is covered by a patent, or patent application in the United States, or a patent, patent application, plant variety protection, or other form of protection, in a foreign country, title to which has been assigned to or otherwise vested in the United States Government.

(b) "Federal agency" means an executive department, military department, Government corporation, or independent establishment, except the Tennessee Valley Authority, which has custody of a Federally owned invention.

(c) "NASA Invention" means a Federally owned invention with respect to which NASA maintains custody and administration, in whole or in part, of the right, title, or interest in such invention on behalf of the United States Government.

(d) "Small business firm" means a small business concern as defined at section 2 of Pub. L. 85-536 (15 U.S.C. 632) and implementing regulations of the Administrator of the Small Business Administration. For the purpose of these regulations, the size standard for small business concerns involved in Government procurement, contained in 13 CFR 121.3-8, and in subcontracting, contained in 13 CFR 121.3-12, will be used.

(e) "Practical application" means to manufacture in the case of a composition or product, to practice in the case of a process or method, or to operate in the case of a machine or system, and, in each case, under such conditions as to establish that the invention is being utilized and that its benefits are to the extent permitted by law or Government regulations available to the public on reasonable terms.

(f) "United States" means the United States of America, its territories and possessions, the District of Columbia, and the Commonwealth of Puerto Rico.

§ 1245.203 Authority to grant licenses.

NASA inventions shall be made available for licensing as deemed appropriate in the public interest. NASA may grant nonexclusive, partially exclusive, or exclusive licenses thereto under this subpart on inventions in its custody.

Restrictions and Conditions

§ 1245.204 All licenses granted under this subpart.

(a) *Restrictions.* (1) A license may be granted only if the applicant has supplied NASA with a satisfactory plan for development or marketing of the invention, or both, and with information about the applicant's capability to fulfill the plan.

(2) A license granting rights to use or sell under a NASA invention in the United States shall normally be granted only to a licensee who agrees that any products embodying the invention or produced through the use of the invention will be manufactured substantially in the United States.

(b) *Conditions.* Licenses shall contain such terms and conditions as NASA determines are appropriate for the protection of the interests of the Federal Government and the public and are not in conflict with law or this subpart. The following terms and conditions apply to any license:

(1) The duration of the license shall be for a period specified in the license agreement, unless sooner terminated in accordance with this subpart.

(2) The license may be granted for all or less than all fields of use of the invention or in specified geographical areas, or both.

(3) The license may extend to subsidiaries of the licensee or other parties if provided for in the license but shall be nonassignable without approval of NASA, except to the successor of that part of the licensee's business to which the invention pertains.

(4) The license may provide the licensee the right to grant sublicenses under the license, subject to the approval of NASA. Each sublicense shall make reference to the license, including the rights retained by the Government, and a copy of such sublicense shall be furnished to NASA.

(5) The license shall require the licensee to carry out the plan for development or marketing of the invention, or both, to bring the invention to practical application within a period specified in the license, and to continue to make the benefits of the invention reasonably accessible to the public.

(6) The license shall require the licensee to report periodically on the utilization or efforts at obtaining utilization that are being made by the licensee, with particular reference to the plan submitted.

(7) All licenses shall normally require royalties or other consideration.

(8) Where an agreement is obtained pursuant to § 1245.204(e)(2) that any products embodying the invention or produced through use of the invention will be manufactured substantially in the United States, the license shall recite such agreement.

(9) The license shall provide for the right of NASA to terminate the license, in whole or in part, if:

(i) NASA determines that the licensee is not executing the plan submitted with its request for a license and the licensee cannot otherwise demonstrate to the satisfaction of NASA that it has taken or can be expected to take within a reasonable time effective steps to achieve practical application of the invention;

(ii) NASA determines that such action is necessary to meet requirements for public use specified by Federal regulations issued after the date of the license and such requirements are not reasonably satisfied by the licensee;

(iii) The licensee has willfully made a false statement of or willfully omitted a material fact in the license application or in any report required by the license agreement; or

(iv) The licensee commits a substantial breach of a covenant or agreement contained in the license.

(10) The license may be modified or terminated, consistent with this subpart, upon mutual agreement of NASA and the licensee.

(11) Nothing relating to the grant of a license, nor the grant itself, shall be construed to confer upon any person any immunity from or defenses under the antitrust laws or from a charge of patent misuse, and the acquisition and use of rights pursuant to this subpart shall not be immunized from the operation of state or Federal law by reason of the source of the grant.

Types of Licenses

§ 1245.205 Nonexclusive licenses.

(a) *Availability of licenses.* Nonexclusive licenses may be granted under NASA inventions without publication of availability or notice of a prospective license.

(b) *Conditions.* In addition to the provisions of § 1245.204, the nonexclusive license may also provide that, after termination of a period specified in the license agreement, NASA may restrict the license to the fields of use or geographic areas, or both, in which the licensee has brought the invention to practical application and continues to make the benefits of the invention reasonably accessible to the public. However, such restriction shall be made only in order to grant an exclusive or partially exclusive license in accordance with this subpart.

§ 1245.206 Exclusive and partially exclusive licenses.

(a) Domestic licenses.

(1) *Availability of licenses.* Exclusive or partially exclusive licenses may be granted on NASA inventions: (i) 3 months after notice of the invention's availability has been announced in the **Federal Register**; or (ii) without such notice where NASA determines that expeditious granting of such a license will best serve the interests of the Federal Government and the public; and (iii) in either situation, specified in (a)(1)(i) or (ii) of this section only if:

(A) Notice of a prospective license, identifying the invention and the prospective licensee, has been published in the **Federal Register**, providing opportunity for filing written objections within a 60-day period;

(B) After expiration of the period in § 1245.206(a) (1)(iii)(A) and consideration of nay written objections received during the period, NASA has determined that:

(*1*) The interests of the Federal Government and the public will best be served by the proposed license, in view of the applicant's intentions, plans, and ability to bring the invention to practical application or otherwise promote the invention's utilization by the public;

(*2*) The desired practial application has not been achieved, or is not likely expeditiously to be achieved, under any nonexclusive license which has been granted, or which may be granted, on the invention;

(*3*) Exclusive or partially exclusive licensing is a reasonable and necessary incentive to call forth the investment of risk capital and expenditures to bring the invention to practical application or otherwise promote the invention's utilization by the public; and

(*4*) The proposed terms and scope of exclusivity are not greater than reasonably necessary to provide the incentive for bringing the invention to practical application or otherwise promote the invention's utilization by the public;

(C) NASA has not determined that the grant of such license will tend substantially to lessen competition or result in undue concentration in any section of the country in any line of commerce to which the technology to be licensed relates, or to create or maintain other situations inconsistent with the antitrust laws; and

(D) NASA has given first preference to any small business firms submitting plans that are determined by the agency to be within the capabilities of the firms and as equally likely, if executed, to bring the invention to practical application as any plans submitted by applicants that are not small business firms.

(2) *Conditions*. In addition to the provisions of § 1245.204, the following terms and conditions apply to domestic exclusive and partially exclusive licenses:

(i) The license shall be subject to the irrevocable, royalty-free right of the Government of the United States to practice and have practiced the invention on behalf of the United States and on behalf of any foreign government or international organization pursuant to any existing or future treaty or agreement with the United States.

(ii) The license shall reserve to NASA the right to require the licensee to grant sublicenses to responsible applicants, on reasonable terms, when necessary to fulfill health or safety needs.

(iii) The license shall be subject to any licenses in force at the time of the grant of the exclusive or partially exclusive license.

(iv) The license may grant the licensee the right of enforcement of the licensed patent pursuant to the provisions of Chapter 29 of Title 35, United States Code, or other statutes, as determined appropriate in the public interest.

(b) Foreign licenses.

(1) *Availability of licenses*. Exclusive or partially exclusive licenses may be granted on a NASA invention covered by a foreign patent, patent application, or other form of protection, provided that:

(i) Notice of a prospective license, identifying the invention and prospective licensee, has been published in the Federal Register, providing opportunity for filing written objections within a 60-day period and following consideration of such objections;

(ii) NASA has considered whether the interests of the Federal Government or United States industry in foreign commerce will be enhanced; and

(iii) NASA has not determined that the grant of such license will tend substantially to lessen competition or result in undue concentration in any section of the United States in any line of commerce to which the technology to be licensed relates, or to create or maintain other situations inconsistent with antitrust laws.

(2) *Conditions*. In addition to the provisions of § 1245.204, the following terms and conditions apply to foreign exclusive and partially exclusive licenses:

(i) The license shall be subject to the irrevocable, royalty-free right of the Government of the United States to practice and have practiced the invention on behalf of the United States and on behalf of any foreign government or international organization pursuant to any existing or future treaty or agreement with the United States.

(ii) The license shall be subject to any licenses in force at the time of the grant of the exclusive or partially exclusive license.

(iii) The license may grant the licensee the right to take any suitable and necessary actions to protect the licensed property, on behalf of the Federal Government.

(c) *Record of determinations*. NASA shall maintain a record of determinations to grant exclusive or partially exclusive licenses.

Procedures

§ 1245.207 Application for a license.

An application for a license should be addressed to the Patent Counsel at the NASA installation having responsibility for the invention and shall normally include:

(a) Identification of the invention for which the license is desired, including the patent application serial number or patent number, title, and date, if known;

(b) Identification of the type of license for which the application is submitted;

(c) Name and address of the person, company, or organization applying for the license and the citizenship or place of incorporation of the applicant;

(d) Name, address, and telephone number of representative of applicant to whom correspondence should be sent;

(e) Nature and type of applicant's business, identifying products or services which the applicant has successfully commercialized, and approximate number of applicant's employees;

(f) Source of information concerning the availability of a license on the invention;

(g) A statement indicating whether applicant is a small business firm as defined in § 1245.202(c);

(h) A detailed description of applicant's plan for development or marketing of the invention, or both, which should include:

(1) A statement of the time, nature and amount of anticipated investment of capital and other resources which applicant believes will be required to bring the invention to practical application;

(2) A statement as to applicant's capability and intention to fulfill the plan, including information regarding manufacturing, marketing, financial, and technical resources;

(3) A statement of the fields of use for which applicant intends to practice the invention; and

(4) A statement of the geographic areas in which applicant intends to manufacture any products embodying the invention and geographic areas where applicant intends to use or sell the invention, or both;

(i) Identification of licenses previously granted to applicant under Federally owned inventions;

(j) A statement containing applicant's best knowledge of the extent to which the invention is being practiced by private industry or Government, or both, or is otherwise available commercially; and

(k) Any other information which applicant believes will support a determination to grant the license to applicant.

§ 1245.208 Processing applications.

(a) Applications for licenses will be initially reviewed by the Patent Counsel of the NASA installation having responsibility for the invention. The Patent Counsel shall make a preliminary recommendation to the Director of Licensing, NASA Headquarters, whether to: (1) grant the license as requested, (2) grant the license with modification after negotiation with the licensee, or (3) deny the license. The Director of Licensing shall review the preliminary recommendation of the Patent Counsel and make a final recommendation to the NASA Assistant General Counsel for Patent Matters. Such review and final recommendation may include, and be based on, any additional information obtained from applicant and other sources that the Patent Counsel and the Director of Licensing deem relevant to the license requested. The determination to grant or deny the license shall be made by the Assistant General Counsel for Patent Matters based on the final recommendation of the Director of Licensing.

(b) When notice of a prospective exclusive or partially exclusive license is published in the Federal Register in accordance with § 1245.206(a)(1)(iii)(A) or § 1245.206(b)(1)(i), any written objections received in response thereto will be considered by the Director of Licensing in making the final recommendation to the Assistant General Counsel for Patent Matters.

(c) If the requested license, including any negotiated modifications, is denied by the Assistant General Counsel for Patent Matters, the applicant may request reconsideration by filing a written request for reconsideration within 30 days after receiving notice of denial. This 30-day period may be extended for good cause.

(d) In addition to, or in lieu of requesting reconsideration, the applicant may also appeal the denial of the license in accordance with § 1245.211.

§ 1245.209 Notice to Attorney General.

A copy of the notice provided for in §§ 1245.206(a)(1)(iii)(A) and 1245.206(b)(1)(i) will be sent to the Attorney General.

§ 1245.210 Modification and termination of licenses.

Before modifying or terminating a license, other than by mutual agreement, NASA shall furnish the licensee and any sublicensee of record a written notice of intention to modify or terminate the license, and the licensee and any sublicensee shall be allowed 30 days after such notice to remedy any breach of the license or show cause why the license should not be modified or terminated.

§ 1245.211 Appeals.

(a) The following parties may appeal to the NASA Administrator or designee any decision or determination concerning the grant, denial, interpretation, modification, or termination of a license:

(1) A person whose application for a license has been denied;

(2) A licensee whose license has been modified or terminated, in whole or in part; or

(3) A person who timely filed a written objection in response to the notice required by §§ 1245.206(a)(1)(iii)(A) or 1245.206(b)(1)(i) and who can demonstrate to the satisfaction of NASA that such person may be damaged by the Agency action.

(b) Written notice of appeal must be filed within 30 days (or such other time as may be authorized for good cause shown) after receiving notice of the adverse decision or determination; including an adverse decision following the request for reconsideration under § 1245.208(c). The notice of appeal, along with all supporting documentation should be addressed to the Administrator, National Aeronautics and Space Administration, Washington, DC 20546. Should the appeal raise a genuine dispute over material facts, fact-finding will be conducted by the NASA Inventions and Contributions Board. The person filing the appeal shall be afforded an opportunity to be heard and to offer evidence in support of the appeal. The Chairperson of the Inventions and Contributions Board shall prepare written findings of fact and transmit them to the Administrator or designee. The decision on the appeal shall be made by the NASA Administrator or designee. There is no further right of administrative appeal from the decision of the Administrator or designee.

§ 1245.212 Protection and administration of inventions.

NASA may take any suitable and necessary steps to protect and administer rights to NASA inventions, either directly or through contract.

§ 1245.213 Transfer of custody.

NASA having custody of certain Federally owned inventions may transfer custody and administration in whole or in part, to another Federal agency, of the right, title, or interest in any such invention.

§ 1245.214 Confidentiality of information.

Title 35, United States Code, section 209, provides that any plan submitted pursuant to § 1245.207(h) and any report required by § 1245.204(b)(6) may be treated by NASA as commercial and financial information obtained from a person and privileged and confidential and not subject to disclosure under section 552 of Title 5 of the United States Code.

James M. Beggs,

Administrator.

October 15, 1981.

[FR Doc. 81-31[illegible] Filed 10-30-81; 8:45 am]

BILLING CODE 7510-01-M

APPENDIX E

PATENT ACQUISITION AND LICENSING STATISTICS

APPENDIX E

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL

STATISTICS
OF THE
NASA PATENT PROGRAM
(FISCAL YEARS 1981 THROUGH 1989)

Page	Contents
SUMS	Summary Statement on Statistics FY 1988
DEF	Definitition of Acronyms and Other Abbreviations
IDY	Invention Disclosures Reported by Year
IDFI	Invention Disclosures Reported by Year and Field Installation
PAS	Summary of Patent Applications Field in the U.S. by Fiscal Year
PAFI	U.S. Patent Applications Filed by NASA by Year and Field Installation
PAFF	Patent Applications Filed Foreign for FY 1989
PTI	Patents Issued in the U.S. by Year
SOI	Status of Inventions
WAS	Waiver Statistics for FY 1989
SES	Small Entity Report Summary by Fiscal Year
LIC	Patent Licenses by Fiscal Year

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
SUMMARY STATEMENT ON STATISTICS

Purpose - The NASA patent program is designed (1) to establish and protect the Government's rights in new technology generated in NASA programs, and (2) to further NASA's mission by using the incentives inherent in the patent system for fostering creation, identification, dissemination and utilization of this new technology.

Policy - NASA's policy with respect to inventions made under contracts, grants and cooperative agreements (with other than small business firms and nonprofit organizations) is based on Section 305 of the National Aeronautics and Space Act of 1958 as amended (42 U.S.C 2457); and, Public Law 96-517 (35 U.S.C. 200 et seq.) for contracts with small business firms and nonprofit organizations.

Section 305 of the Space Act is unique to NASA in that NASA acquires title to all inventions made under its contracts with other than small business firms and nonprofit organizations unless the Administrator determines that the public interest would be served by waiving title to the contractor. The Statements of Government Patent Policy issued on August 23, 1971, and February 18, 1983, are used as guides in applying this waiver authority. The Patent Waiver Regulations are found at 14 CFR 1245.1 and the Federal Register of November 16, 1987, pages 43748 to 43753.

The disposition of rights to inventions made under contracts with small firms and nonprofit organizations is governed by Public Law 96-517, effective July 1, 1981. This law allows the contractor, who meets the definition of a small business or nonprofit organization, the first option to retain title to inventions made under contract, provided such contractor follows the procedures prescribed in the law.

Rights to NASA employee inventions are allocated in accordance with Presidential Executive Order 10096, issued in 1950, and 37 CFR Part 501 of November 1, 1988, which has Government-wide application.

The NASA statistics for the operation of the Jet Propulsion Laboratory by the California Institute of Technology are included in the overall small entity numbers, but also separately shown. To not include the numbers for CIT/JPL as separate statistics could be misleading due to the large number of inventions reported from this one contractor.

PAGE SUMS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL

DEFINITION OF ACRONYMS AND OTHER ABBREVIATIONS USED IN THESE STATISTICS

FY	Fiscal Year - A period from October 1 of a year to September 30 of the following year
SE	Small Entity is a non-profit organization, a college or university or small business. (See definitions of 35 U.S.C. Section 201 and P.L. 96-517).
LE	Large Entity is a firm, corporation, etc. subject to Section 305 of the National Aeronautics and Space Act of 1958, as amended, (42 U.S.C. Section 2457) and not a Small Entity.
GE	Government Employee
CIT/JPL	California Institute of Technology/Jet Propulsion Laboratory
NRO-JPL	NASA Resident Office at the Jet Propulsion Laboratory
IDY	Invention disclosures reported by year
KOR	Means contractor
ARC	The NASA field installation, Ames Research Center at Moffett Field, California
DFRF	Dryden Flight Research Facility at Edwards, California
GSFC	The NASA field installation, Goddard Space Flight Center at Greenbelt, Maryland
HDQS	NASA Headquarters, Washington, DC
JSC	The NASA field installation, Lyndon B. Johnson Space Center at Houston, Texas
KSC	The NASA field installation, John F. Kennedy Space Center at Kennedy Space Center, Florida
LARC	The NASA field installation, Langley Research Center at Hampton, Virginia.

LERC	The NASA field installation, Lewis Research Center at Cleveland, Ohio
MSFC	The NASA field installation, George C. Marshall Space Flight Center at Marshall Space Flight Center, Alabama
EPC	European Patent Convention

Section 305 Space Act - 42 U.S.C. Section 2457, Property Rights in Inventions (P.L. 85-568, July 29, 1958)

P.L. 96-517 - 35 U.S.C. Section 200 et seq., Patent Rights in Inventions Made with Federal Assistance, December 12, 1980

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
INVENTION DISCLOSURES REPORTED BY FISCAL YEAR

FISCAL YEAR	EMPLOYEE[1]	LARGE ENTITY CONTRACTORS[2]	SMALL ENTITY CONTRACTORS		TOTAL
			EXCEPT CIT/JPL[3]	CIT/JPL[4]	
1981	216	954	0	0	1,170
1982	176	760	6	0	942
1983	211	783	20	88	1,102
1984	225	549	43	148	965
1985	192	421	72	177	862
1986	184	447	93	223	947
1987	233	434	83	263	1,013
1988	242	461	115	220	1,038
1989	256	530	154	276	1,216

[1] Inventions subject to 37 CFR 501, E.O. 10096.

[2] Inventions reported and subject to Section 305(a), Space Act of 1958, as amended (42 U.S.C. 2457).

[3] Inventions reported under P.L. 96-517 (35 U.S.C. 200 et seq), except CIT/JPL.

[4] Inventions reported by CIT/JPL under P.L. 96-517.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
INVENTION DISCLOSURES REPORTED BY YEAR AND FIELD INSTALLATION - FISCAL YEAR

Installation		1981*	1982	1983	1984	1985	1986	1987	1988	1989
ARC	CE	29	19	18	37	23	20	28	15	21
	LE	39	37	33	41	41	12	40	33	43
	SE	0	0	2	9	5	0	3	5	0
DFRF	CE	0								
	LE	5	**	**	**	**	**	**	**	**
	SE	0								
GSFC	CE	26	27	25	18	13	19	13	24	16
	LE	37	23	23	19	21	21	19	17	13
	SE	0	0	0	1	9	12	13	9	13
HDQS	CE	1	4	4	0	0	1	0	0	0
	LE	7	3	4	2	0	0	0	3	1
	SE	0	0	0	1	10	4	1	9	10
JSC	CE	18	12	13	10	25	16	22	36	45
	LE	287	207	283	137	137	169	87	62	96
	SE	0	0	0	4	1	9	17	13	35
KSC	CE	4	8	4	9	29	5	10	5	26
	LE	23	30	23	9	11	14	12	21	30
	SE	0	0	1	2	3	10	4	6	9
LaRC	CE	30	44	36	32	32	45	100	83	63
	LE	40	32	61	43	24	48	30	40	66
	SE	0	3	9	10	13	31	21	44	39
LeRC	CE	47	42	42	38	31	40	37	41	33
	LE	40	76	67	42	41	33	22	37	35
	SE	0	1	1	3	12	9	3	7	13
MSFC	CE	28	21	49	43	17	30	23	30	34
	LE	105	64	131	107	148	130	197	220	226
	SE	0	0	7	13	19	10	19	22	25
NMO-JPL	CE	0	0	0	0	0	0	0	0	0
	LE	350	259	130	63	6	0	7	0	0
	SE	0	0	80	148	177	223	203	220	276
TOTAL		1,170	942	1,102	964	882	967	1,013	1,030	1,216

* P.L. 96-517 Effective July 1, 1981.

** DFRF included in ARC report.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
SUMMARY OF PATENT APPLICATIONS FILED IN THE U.S. - FISCAL YEAR

FISCAL YEAR	FILED BY NASA					TOTAL	FILED BY CONTRACTOR/ GOV'T HAS LICENSE		GRAND TOTAL
	GOV'T EMPLOYEE	CONTRACTOR EMPLOYE			GOV'T EMPLOYEE/ GOV'T HAS LICENSE		SPACE ACT §305 WAIVER APPLICABLE - LE FILED	P.L. 96-517 APPLICABLE - SE FILED	
		LE	SE OTHER	SE CIT/JPL					
1981*	98	72	0	0	1	171	39	0	210
1982	89	100	0	0	1	190	35	2	227
1983	83	83	0	3	0	169	33	5	207
1984	76	48	5	5	1	135	20	10	168
1985	63	34	12	19	0	128	30	24	182
1986	61**	27	7	18	2	115	39	24	178
1987	69	30	10	24	1	134	28	23	182
1988	85	28	17	43	1	174	31	28	233
1989	80	17	19	34	0	150	16	23	189

* P.L. 96-517 effective July 1, 1981.

** Includes one application converted to a Statutory Invention Registration.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
U.S. PATENT APPLICATIONS FILED BY NASA BY YEAR AND FIELD INSTALLATION - FISCAL YEAR

INSTALLATION	1981*	1982	1983	1984	1985	1986	1987	1988	1989
ARC	9	13	19	18	20	14	7	7	9
DFRF	3	**	**	**	**	**	**	**	**
GSFC	21	20	15	9	5	7	4	7	11
HDQS	0	1	0	0	0	0	0	0	0
JSC	16	23	7	13	11	12	21	29	16
KSC	1	2	0	2	1	2	1	1	3
LARC	28	35	33	30	31	41	55	64	34
LERC	32	22	26	22	12	8	7	7	14
MSFC	21	26	22	14	17	13	13	16	23
NRO-JPL	40	48	47	27	31	18	26	43	38
TOTALS	171	190	169	135	128	115	134	174	148

* P.L. 96-517 effective July 1, 1981.
** Included in ARC Report.

PAGE PAFI

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
FOREIGN PATENT APPLICATIONS FILED IN FISCAL YEAR 1989

CASE NO.	NO. OF COUNTRIES DESIGNATED	TITLE
ARC 11,873-1	13	(PCT: Japan, South Korea and Europe) Improved Etching Process for Photo Resists or Polymers
LAR 13,761-1	12	(PCT: Japan and Europe) Reusable Heat Pipes and Heat Pipe Panels
LAR 13,774-1	15	(PCT: Australia, Japan, South Korea and Europe; Canada) Quick Actuating Closure
LAR 13,819-1NP	15	(PCT: Japan, Europe, Australia and South Korea; Canada) Process for Preparing Trisaryloxycyclo-triphosphazene Polymer Precursors and Intermediates
LAR 13,902-1	15	(PCT: Australia, Japan, Europe and South Korea; Canada) Process for Lowering the Dielectric Constant of Polyimides Using Diamic Acid Additives
LAR 13,910-1CU	1	(Canada) Ethynl Terminated Imidothioethers and Resins Therefrom
LAR 13,924-1	1	(Canada) Aluminum Alloy
LAR 13,925-1	1	(Canada) Semi-Interpenetrating Polymer Network for Tougher and more Microcracking Resistant High Temperature Polymers
LAR 13,952-1SB	1	(Canada) Method and Apparatus for Detecting Laminar Flow Separation and Reattachment
LAR 13,958-1	15	(PCT: Australia, Japan, South Korea and Europe; Canada) Tough, High Performance, Addition-Type Thermoplastic Polymers
LAR 13,992-1CU	15	(PCT: Japan, Australia, Europe, and South Korea; Canada) Low Dielectric Fluorinated Poly-(Phenylene Ether Ketone) Film and Laminate

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
FOREIGN PATENT APPLICATIONS FILED IN FISCAL YEAR 1989 (CONT.)

CASE NO.	NO. OF COUNTRIES DESIGNATED	TITLE
LAR 14,101-1	13	(PCT: Japan, Australia and Europe; Canada) Processable Polyimide Adhesive and Matrix Composite Resin
MFS 28,282-1	13	(PCT: Japan, Australia and Europe) Planar Thin Film Squid with Integral Flux Concentrator
MSC 21,293-1	13	(PCT: Japan, Australia, and Europe) Bio-reactor Cell Culture and Process
Total Number of Inventions is 14	143*	

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* Differs from the total number of inventions (in U.S. patent applications) due to the European Patent Convention, i.e., a single U.S. patent application filed as an EPC application, may designate applications to be filed in a plurality of countries.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
PATENTS ISSUED IN THE U.S.

FISCAL YEAR	FILED BY NASA				TOTAL	FILED BY CONTRACTOR/ GOV'T HAS LICENSE		GRAND TOTAL
	GOV'T EMPLOYEE	CONTRACTOR EMPLOYEE		GOV'T EMPLOYEE/ GOV'T HAS LICENSE		SPACE ACT §305 WAIVER APPLICABLE - LE FILED	P.L. 96-517 APPLICABLE - SE FILED	
		LE	SE					
1981*	61	88	0	0	149	23	0	172
1982	59	55	0	0	114	22	0	136
1983	80	51	0	1	132	11	0	143
1984	83	60	0	1	144	16	0	160
1985	70	69	0	0	139	23	3	165
1986	64	38	7	1	110	9	5	124
1987	55	36	22	1	114	13	12	139
1988	49	20	28	1	98	14	8	120
1989	55	26	44	1	127	21	28	176

*P.L. 96-517 Effective July 1, 1981.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
STATUS OF INVENTIONS - FISCAL YEAR 1989

INSTALLATIONS	DISCLOSURES RECEIVED	DISCLOSURES INACTIVATED	DISCLOSURES UNDER EVAL/SEARCH*	AWAITING PREPARATION OF PATENT APPLICATIONS*	APPLICATIONS UNDER PROSECUTION*	PATENTS ISSUED
ARC	72	24	0	0	17	11
DFRF	(Docket maintained at the Ames Research Center)					
GSFC	42	6	52	21	16	6
HDQS	11	11	1	0	0	0
JSC	176	123	52	19	41	24
KSC	83	0	125	3	3	2
LARC	168	69	224	60	110	26
LERC	83	59	82	18	22	3
MSFC	303	147	6	8	21	14
NRO-JPL	278	212	11	27	78	29
TOTAL	1216	651	566	156	307	125

License 2

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*As of the end of the Fiscal Year

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL
FISCAL YEAR WAIVER STATISTICS

FOR LARGE ENTITY (Section 305 SPACE ACT) CONTRACTORS

	1984	1985	1986	1987	1988	1989
I. Petitions for Individual Inventions						
1. Petitions for waiver received*	91	73	53	70	53	28
a. Domestic			32	41	33	19
b. Foreign		21	29	22	09	09
2. Petitions granted**	67	76	49	55	71	28
a. Domestic			29	35	42	19
b. Foreign			20	20	29	09
3. Petitions denied	00	00	00	00	00	00
a. Domestic	00	00	00	00		
b. Foreign			00	00	00	00
4. Petitions withdrawn	07	10	04	02	04	02
a. Domestic			03	01	04	01
b. Foreign			03	01	00	01
II. Petitions for Advance Waivers						
1. Petitions for waiver received*	64	55	42	42	48	15
a. Domestic			24	22	25	08
b. Foreign			18	20	23	07
2. Petitions granted	47	48	37	31	50	26
a. Domestic			32	16	26	14
b. Foreign			25	15	24	12
3. Petitions denied	05	00	00	00	00	00
a. Domestic			00	00	00	00
b. Foreign			00	00	00	00
4. Petitions withdrawn	04	06	04	11	02	00
a. Domestic			02	06	01	00
b. Foreign			02	05	01	00

III. Other Statistics

1. Inventions reported by NASA LE contractors (other than SE small business and nonprofit organizations). 530
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* A petitioner may request domestic rights only, foreign rights only, or both. A petition for both domestic and foreign rights is recorded as two (2) petitions.

** The petitions granted may exceed the petitions received in that the petitions granted are usually from more that one fiscal year.

*** If foreign patent applications were filed as well as a domestic patent application on the same invention, it is recorded as one (1) invention.

**** Voiding actions include the voiding of a waiver of title, either domestic and/or foreign. Entire waivers may be voided or portions of waivers may be voided in foreign waivers wherein the waiver recipient chooses to abandon and/or transfer the rights to less than all the countries.

IN ANALYZING THESE STATISTICS IT IS IMPORTANT TO DISTINGUISH BETWEEN
PETITIONS AND INVENTIONS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF GENERAL COUNSEL

SMALL ENTITY REPORT SUMMARY BY FISCAL YEAR
(P.L. 96-517 AND OMB CIRCULAR A-124)

	FY83	FY84	FY85	FY86	FY87	FY88	FY89
1. Inventions Reported By:							
a. Small Business Firms	004	014	026	026	039	059	089
b. Nonprofit Organization	001	003	003	004	008	002	000
c. College or University							
(1) Except CIT/JPL	015	026	043	052	036	034	057
(2) CIT/JPL	088	148	177	223	263	220	276
TOTAL	108	191	249	305	346	335	430
2. Number of Inventions SE Elected to Retain Title:							
a. Small Business Firms	002	002	003	009	014	014	029
b. Nonprofit Organization	000	000	001	001	001	000	000
c. College or University							
(1) Except CIT/JPL	002	008	017	014	013	021	006
(2) CIT/JPL	004	013	013	008	035	055	009
TOTAL	008	023	034	032	063	090	044
3. Patent Applications Filed by Small Entities:							
a. Small Business Firms	002	001	003	006	011	010	009
b. Nonprofit Organization	000	000	000	002	001	001	001
c. College or University							
(1) Except CIT/JPL	000	006	010	006	009	009	000
(2) CIT/JPL	003	003	011	010	002	008	013
TOTAL	005	010	024	024	023	028	023
4. Patents Issued to Small Entities:							
a. Small Business Firms	000	000	000	000	003	002	006
b. Nonprofit Organization	000	000	000	000	001	000	000
c. College or University							
(1) Except CIT/JPL	000	000	003	003	003	003	007
(2) CIT/JPL	000	000	000	002	005	003	013
TOTAL	000	000	003	005	012	008	026
5. If Small Entity Did Not Elect Title, How Many Patent Applications Did NASA File on These Inventions?							
a. All Small Entities Except CIT/JPL	000	005	012	007	010	017	007
b. CIT/JPL	003	005	019	018	024	043	041
TOTAL	003	010	031	025	034	060	048

3/12/90

LICENSING STATISTICS

Fiscal Year	Domestic Exclusive	Domestic Nonexclusive	Foreign Exclusive	Foreign Nonexclusive	Technical Assistance
1982	10	24	0	4	0
1983	8	18	0	2	0
1984	10	18	5	2	0
1985	6	5	0	0	0
1986	5	5	2	0	0
1987	8	9	2	0	0
1988	4	3	0	0	1
1989	5	1	0	0	0

(16)

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of L:DCL:brb

NOV 2 1990

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed for the information of the Committee is a copy of a letter recently sent to the Speaker of the House transmitting NASA's 1990 report on the state of our knowledge of the Earth's upper atmosphere.

Sincerely,

Martin P. Kress

Martin P. Kress
Assistant Administrator
for Legislative Affairs

Enclosures

cc: Honorable Robert S. Walker

NASA
National Aeronautics and
Space Administration

Washington, D C
20546

Office of the Administrator

OCT 25 1990

Honorable Thomas S. Foley
Speaker of the House
Washington, DC 20515

Dear Mr. Speaker:

Pursuant to the Clean Air Act Amendments of 1977, P.L. 95-95, I am pleased to transmit the NASA biennial report on the state of our knowledge of the Earth's upper atmosphere.

This report presents new findings since the last report issued in 1988. Part I, dated January 1990, summarizes the research efforts supported by NASA under the Upper Atmosphere Research Program, including theoretical studies and data analysis activities. Part II, "Present State of Knowledge of the Upper Atmosphere 1990: An Assessment Report," dated September 1990, presents several scientific assessments of our current understanding of the chemical composition and physical structure of the stratosphere, in particular the manner in which the abundance and distribution of ozone are predicted to change in the future.

Sincerely,

Richard H. Truly
Administrator

Enclosures

NASA
Reference
Publication
1242

1990

Present State of Knowledge of the Upper Atmosphere 1990: An Assessment Report

Report to Congress

R. T. Watson,
M. J. Kurylo,
M. J. Prather,
and F. M. Ormond
NASA Office of Space Science and Applications
Washington, D.C.

National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division

R. T. Watson and D. L. Albritton, Co-Chairs, *International Scientific Assessment of Stratospheric Ozone: 1989*

M. J. Prather and R. T. Watson, *Transient Scenarios for Atmospheric Chlorine and Bromine*

M. J. Kurylo, R. F. Hampson, and the NASA Panel for Data Evaluation, *Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling*

M. J. Prather et al., *An Assessment of the Impact on Stratospheric Chemistry and Ozone Caused by the Launch of the Space Shuttle and Titan IV*

High Speed Research Program Atmospheric Advisory Committee, *The Atmospheric Effects of Stratospheric Aircraft*

Preface

NASA has relied heavily on the entire scientific community, national and international, in its effort to provide a better understanding of the upper atmosphere and its perturbation in response to natural phenomenon and human activities. The lists of contributors to the individual sections in this report are given in Section G. We are indebted to those who gave their time and knowledge.

Robert T. Watson

Michael J. Kurylo

Michael J. Prather

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SECTION A

INTRODUCTION

In compliance with the Clean Air Act Amendments of 1977, Public Law 95-95, the National Aeronautics and Space Administration (NASA) has prepared this Report on the state of our knowledge of the Earth's upper atmosphere, and particularly, of stratospheric ozone. The Report for the year 1990 presents new findings since the last Report in 1988 and is printed in two parts. Part I (Research Summaries) was issued earlier in this year and summarized the objectives, status, and accomplishments of the research tasks supported under NASA's Upper Atmosphere Research Program (UARP). Part II (this document) presents several scientific assessments of our current understanding of the chemical composition and physical structure of the stratosphere, in particular how the abundance and distribution of ozone is predicted to change in the future. These reviews include: (Section B) a summary of the most recent international assessment of stratospheric ozone; (Section C) a study of future chlorine and bromine loading of the atmosphere; (Section D) a review of the photochemical and chemical kinetics data that are used as input parameters for the atmospheric models; (Section E) a new assessment of the impact of Space Shuttle launches on the stratosphere; (Section F) a summary of the environmental issues and needed research to evaluate the impact of the newly re-proposed fleet of stratospheric supersonic civil aircraft; and (Section G) a list of the contributors to this Report.

For two decades scientists have postulated that certain pollutants directly associated with human activity could cause harmful effects by reducing the amount of stratospheric ozone. Initial concerns focussed on supersonic aircraft emissions of NO and NO_2, and then shifted to the issue of chlorine loading of the stratosphere from chlorofluorocarbons (CFCs). In recognition of the importance of understanding such perturbations, Congress directed NASA in June 1975 to "develop and carry out a comprehensive program of research, technology, and monitoring of the phenomena of the upper atmosphere so as to provide for an understanding of and to maintain the chemical and physical integrity of the Earth's upper atmosphere".

Responding to this Congressional mandate, NASA implemented a long-range scientific research program, the UARP, aimed at developing a comprehensive understanding of processes in the upper atmosphere. In the near-term NASA has the responsibility of providing biennial reports to the Congress and concerned regulatory agencies on the status of upper atmospheric research, including scientific assessments of potential effects of human activities on the atmosphere, and particularly, on stratospheric ozone.

Many governments around the world, including the United States, have recognized that the ozone layer must be protected in order to protect human health and aquatic and terrestrial ecosystems from damage due to enhanced levels of ultraviolet radiation. In particular, it was recognized that the use of chemicals containing chlorine (in the form of chlorofluorocarbons, CFCs) and bromine (in the form of halons) constitute a potential threat to the stability of the ozone layer. More than twenty nations, including the United States, signed the Vienna Convention for the Protection of the Ozone Layer in Vienna, Austria, in March 1985, and the Montreal Protocol on Substances that Deplete the Ozone Layer, in Montreal, Canada, in September 1987. The United States and 46 other nations (as of November 1989) have subsequently ratified both the Vienna Convention and the Montreal Protocol. The Vienna Convention and the Montreal Protocol both call for all regulatory decisions to be based on a scientific understanding of the issues, and specifically the Montreal Protocol called for an international scientific assessment in 1989 in preparation for the 1990 policy review.

Introduction

The 1989 scientific assessment was coordinated by NASA, the National Oceanic and Atmospheric Administration (NOAA), the United Kingdom Department of the Environment (DOE), the United Nations Environment Program (UNEP), and the World Meteorological Organization (WMO). This report was written and peer reviewed by more than 75 scientists from 23 countries, who are regarded as experts in their respective fields. During this period, fifteen CFC-producing companies from around the world organized and sponsored the Alternative Fluorocarbon Environmental Acceptability Study (AFEAS). The AFEAS work similarly involved the international scientific community and was extensively peer reviewed; its results contributed to the ozone assessment and became a companion volume. The "Scientific Assessment of Stratospheric Ozone: 1989" was published this year as WMO Report No. 20. The executive summaries of the 4 assessment chapters (Volume I) and of the AFEAS report (Volume II) are reproduced here in Section B.

During the process of re-evaluating and amending the Montreal Protocol at UNEP meetings in Nairobi (August 1989) and Geneva (November 1989), the need to compare the impact of different policy options arose. The relative atmospheric response over the next 10 to 100 years had to be evaluated, considering a large range of political options to limit production of CFCs, other chlorocarbons, and halons. Drs. Watson and Prather used the results of the international assessment (Section B) to prepare a criteria document that demonstrated the time-dependent growth and decay of atmospheric chlorine and bromine in response to different controls over halocarbons. This document clarified approaches to achieving environmental goals (i.e., limit peak chlorine, removing the Antarctic ozone hole) and was incorporated into the UNEP proceedings as Annex II. It is reproduced here as Section C. The biennial review of the status of kinetics and photochemistry by the NASA Panel for Data Evaluation is an important document for the atmospheric sciences community. It provides a regular focus that brings together the laboratory measurements and the theoretical studies and establishes a reference standard for atmospheric modelling. The most recent recommendations of this panel are published as JPL 90-1 "Chemical Kinetics and Photochemical Data for use in Stratospheric Modeling," and reproduced as Section D in this Report.

The impact of chlorine from the Space Shuttle exhaust has been reexamined because of the clear evidence that atmospheric chlorine increases have led to the formation of the Antarctic ozone hole as well as the much smaller decline over northern mid-latitudes (see Section B). Data on the emissions from the solid rocket motors was supplied by the Thiokol Corporation and three modelling groups simulated the magnitude of the perturbation to stratospheric chlorine levels. Results from all models show that individual launches, or a launch frequency of about one per month, would lead to small (<1 %) perturbations to the background stratospheric chlorine. Larger uncertainty exists regarding the impact of the added burden of stratospheric aerosols from the launch of all types of space vehicles. This study was peer reviewed and is presented in Section E.

Renewed commercial interest in a fleet of supersonic civil aircraft has led to the formation of a research program within NASA to evaluate the environmental and technical issues of supersonic aircraft. A key component of this High Speed Research Program (HSRP) involves evaluation of the atmospheric effects of these stratospheric aircraft, particularly the potential depletion of ozone caused by engine exhaust. The Upper Atmosphere Research Program is working with the HSRP and is overseeing the atmospheric assessment of supersonic civil aircraft. An international scientific advisory panel has been convened by the UARP to provide the scientific guidance that will be needed for a full evaluation of the effects of stratospheric pollution by aircraft. That panel drafted a statement of research needs that formed the basis of the NASA Research Announcement (NRA-89-OSSA-16) that initiated this study in 1989. The research plan is summarized in Section F. Contributors are listed in Section G.

SECTION B

Scientific Assessment of Stratospheric Ozone: 1989

VOLUME I

I. Introduction
II. Executive Summary
III. Scientific Summaries
    1. Polar Ozone
    2. Global Trends
    3. Model Predictions
    4. Halocarbon Ozone Depletion and Global Warming Potentials

VOLUME II - THE AFEAS REPORT

I. Summary
II. Physical Properties
III. Reaction Rate Constants
IV. Absorption Cross Sections
V. Tropospheric OH and HCFC/HFC Lifetimes
VI. Degradation Mechanisms
VII. Liquid Phase Processes
VIII. Ozone Depletion Potentials
IX. Halocarbon Global Warming Potentials
X. Impact on Photochemical Oxidants including Tropospheric Ozone
XI. Natural Sources
XII. Biological and Health Effects

SECTION B

SCIENTIFIC ASSESSMENT OF STRATOSPHERIC OZONE: 1989
Volume I

I. SUMMARY

The *Scientific Assessment of Stratospheric Ozone: 1989* is a scientific review of the current understanding of stratospheric ozone, prepared by international scientific experts who are leaders in their respective fields. This is a summary of its major points.

The aims of this summary section are threefold. The Executive Summary (Sec. II) is a digest of the key points of the *Assessment* and is directed at government officials, the private sector, and the general public. The Scientific Summaries (Sec. III) of each of the four chapters contain the major research findings of the *Assessment* and are directed to the scientific community.

In Section G, the numerous contributors to the preparation of the *Assessment* are identified. The success of the *Assessment* rests on the prodigious efforts and dedication of these people.

This introductory section briefly gives the background to the *Assessment*, its scientific scope, and its place in the current discussions of public policies regarding the protection of the stratospheric ozone layer.

1. Background

The goals, scope, contents, authors, and timetable of the *Assessment* were planned at two international meetings:

- The first was part of a two-day meeting, "Scientific Review of Ozone Layer Modification and Its Impact," which was held at The Hague, The Netherlands, 17-18 October 1988. There were about 70 international scientific attendees at this first of a series of meetings sponsored by the United Nations Environment Program (UNEP). About half of these attendees were involved in the subgroup that focused on defining the scope of the *Assessment* and establishing a scientific steering group.
- The second meeting occurred on 29 November 1988 at the U. K. Department of the Environment in London. Fourteen scientists attended, coming from eight countries, as well as representation from UNEP and the World Meteorological Organization (WMO). The focus of this Steering Committee was on establishing the structure, authors, and timetable of the *Assessment*.

The preparation of the *Assessment* document occurred over the period from January to June, 1989. Numerous scientists from 25 countries were involved either as authors, contributors, or reviewers (see Appendix). Their professional institutions included universities, government laboratories, and the private sector. A review draft was available on 15 June 1989 and was circulated worldwide for comment. This draft was discussed and evaluated at a review meeting at

Les Diablerets, Switzerland on 10-14 July 1989, sponsored by WMO. Forty-three scientists from 14 countries were in attendance and many others participated via mail reviews. Those suggestions and comments have been incorporated into the present final version.

2. Scientific Scope

The focus of the *Assessment* is on four major current aspects of stratospheric ozone: (1) polar ozone, (2) global trends, (3) theoretical predictions, and (4) halocarbon ozone depleting potentials and global warming potentials. Other ozone-related topics are also included: (i) the trends of stratospheric temperature, stratospheric aerosols, source gases, and surface ultraviolet radiation and (ii) the oxidizing capacity of the troposphere as it pertains to the lifetimes of ozone-related chemicals (e.g., the partially halogenated compounds that can serve as shorter-lived substitutes for the long-lived, fully halogenated ozone-depleting gases).

The *Assessment* is an update of the comprehensive "Atmospheric Ozone: 1985" (WMO Report No. 16, 1986) and builds upon the recent "International Ozone Trends Panel Report: 1988" (WMO Report No. 18, in press). It focuses on the results of subsequent recent research and the implications for the stratosphere. The ozone research of the past few years has been remarkable. Several major ground-based and airborne field campaigns have explored the recently discovered Antarctic ozone "hole," as well as the Arctic ozone layer. New laboratory studies of gas-phase and surface-induced chemical processes have provided a better characterization of the polar phenomena. Statistical analyses of hemispheric data sets have revealed significant ozone trends for the first time. Theoretical investigations have aided the interpretation of all of these findings. The picture contained in the *Assessment* reveals a new and deeper understanding of the influence of human activities on the Earth's protective ozone layer.

3. Relation to Public Policy

While the *Assessment* is a scientific document, it also will be useful as essential scientific input to policy decisions regarding the safeguarding of the ozone layer, just as was its predecessor documents (e.g., "Atmospheric Ozone: 1985"). In that regard, one of the most noteworthy applications of the *Assessment* will be the forthcoming international review of the Montreal Protocol on Substances that Deplete the Ozone Layer. Indeed, the above timetable was planned such that the international ozone scientific community can provide that service in the form of the *Assessment*. The Executive Summary of the present document has been written with this need to communicate the state of ozone science in mind.

At the meeting in October 1988 at The Hague, UNEP established four panels to review the current scientific, environmental, technical, and economic information relative to possible amendments to the Montreal Protocol. The *Scientific Assessment of Stratospheric Ozone: 1989* is the report of the first of these panels. There are corresponding reports from the three other panels. The main findings of all four reports were presented to a Working Group meeting in Nairobi, Kenya, on 28 August - 5 September 1989, where the reports were reviewed. Their integration into a single document will be completed, and the resulting integrated report will serve as key input for considerations of possible draft amendments to the Montreal Protocol.

II. EXECUTIVE SUMMARY

1. Recent Findings

The past few years have been remarkable insofar as stratospheric ozone science is concerned. There have been highly significant advances in the understanding of the impact of human activities on the Earth's protective ozone layer. Since the last international scientific review (1985), there are four major findings that each heighten the concern that chlorine- and bromine-containing chemicals can lead to a significant depletion of stratospheric ozone:

- Antarctic Ozone Hole: The weight of scientific evidence strongly indicates that chlorinated (largely man-made) and brominated chemicals are primarily responsible for the recently discovered substantial decreases of stratospheric ozone over Antarctica in springtime.

- Perturbed Arctic Chemistry: While at present there is no ozone loss over the Arctic comparable to that over the Antarctic, the same potentially ozone-destroying processes have been identified in the Arctic stratosphere. The degree of any future ozone depletion will likely depend on the particular meteorology of each Arctic winter and future atmospheric levels of chlorine and bromine.

- Long-Term Ozone Decreases: The analysis of the total-column ozone data from ground-based Dobson instruments show measurable downward trends from 1969 to 1988 of 3 to 5% (i.e., 1.8-2.7% per decade) in the Northern Hemisphere (30 to 64°N latitudes) in the winter months that cannot be attributed to known natural processes.

- Model Limitations: These findings have led to the recognition of major gaps in theoretical models used for assessment studies. Assessment models do not simulate adequately polar stratospheric cloud (PSC) chemistry or polar meteorology. The impact of these shortcomings for the prediction of ozone depletion at lower latitudes is uncertain.

2. Supporting Evidence and Other Results

These and other findings are based upon the results from several major ground-based and aircraft field campaigns in the polar regions, a reanalysis of ground-based ozone data from the past thirty-one years, a reanalysis of satellite ozone and PSC data, laboratory studies of gas-phase and surface-induced chemical processes, and model simulations incorporating these new laboratory data and observations. The highlights and conclusions from these activities in four research areas are summarized below.

Polar Ozone

- *There has been a large, rapid, and unexpected decrease in the abundance of springtime Antarctic ozone over the last decade.*

  Beginning in the late 1970s, total column ozone decreases (lately reaching 50%) have been observed by both ground-based and satellite techniques, the latter showing that the loss is a continental-scale phenomenon. Ozonesondes at several stations have shown that the ozone loss occurs between 12 and 24 km, reaching as much as 95% at some altitudes.

- *The weight of scientific evidence strongly indicates that man-made chlorine and bromine compounds are primarily responsible for the ozone loss in Antarctica.*

  The ozone loss over Antarctica is initiated by chemical reactions that occur on the surfaces of PSCs and that convert the long-lived chlorine into chemically more-reactive forms. Laboratory studies have provided important evidence that such chemical reactions can occur on PSC surfaces. Furthermore, reactions can also remove reactive nitrogen species, thereby slowing the reformation of the less reactive chlorine compounds. Satellite data show that the frequency of occurrence of PSCs is the highest in the Antarctic stratosphere. Indeed, the abundance of the reactive chlorine compounds is observed to be elevated by 50 to 100 times in springtime. The observed reactive chlorine and bromine abundances explain a substantial fraction (60 to 100%) of the rapid ozone loss observed following the return of sunlight to Antarctica in September, 1987.

- *While the onset of the Antarctic ozone hole is linked to the recent growth in the atmospheric abundance of chlorofluorocarbons (CFCs) and to a lesser extent bromine compounds, many of its features are influenced by meteorological conditions.*

  Within the strong circumpolar vortex over Antarctica, temperatures are very low during the winter and spring and there is abundant production of PSCs. These special meteorological conditions set the stage for the occurrence of the ozone hole.

  The year-by-year variability in the depth of the ozone hole appears to be related, in part, to the Quasi-Biennial Oscillation (QBO), which is a natural oscillation of equatorial stratospheric winds. For example, there was a very deep ozone hole in 1987, but it was substantially less deep in 1988, possibly influenced by the observed temperature extremes between the years, which modulated the abundance of PSCs. Tropospheric weather systems can also influence stratospheric temperatures and water vapor on regional scales, which would in turn influence PSC abundance and ozone changes.

- *The chemical composition of the Arctic stratosphere was found to be highly perturbed.*

  The chemical perturbations in the Arctic were similar to those found in Antarctica, namely, an increase in the abundance of the ozone depleting forms of chlorine in association with PSCs. The studies conducted in January and February in 1989 found that the reactive chlorine abundances were enhanced by a factor of 50 to 100. No unambiguous evidence for ozone loss has yet been identified for the winter of 1988/1989. Readily detectable ozone reductions would be expected during January and February only if high concentrations of reactive chlorine species were maintained for sufficiently long periods in cold, illuminated air. The degree of Arctic ozone depletion will be influenced by the year-by-year timing of the warming of the polar vortex relative to the arrival of sunlight, as well as future chlorine and bromine abundances. In the Antarctic, the warming of the polar vortex always occurs after the arrival of sunlight (hence, ozone depletion), which contrasts with the Arctic, where warming generally occurs prior to the arrival of sunlight, as in 1989.

Global Trends

- *Several recent analyses of total column ozone data support the conclusion of the 1988 International Ozone Trends Panel (OTP) that there is a downward trend in ozone during winter at mid-to-high latitudes in the Northern Hemisphere over the past two decades.*

  The OTP analyzed the re-evaluated data from the ground-based Dobson instruments for the effects of known natural geophysical processes (seasonal variability, the approximately 28-month QBO, and the 11-year solar cycle) and possible human perturbations. After allowing for natural variability, the analysis showed measurable decreases in the range of 2.3 to 6.2% between 30 and 64°N latitude for the winter months (December - March) between 1969 and 1986, with the larger decreases being at the higher latitudes. This was the first analysis that showed statistically significant downward trends.

The results of model calculations of chlorine-induced ozone loss are broadly consistent with these observed latitudinal and seasonal changes in column ozone, except that the mean values of the observed decreases at mid- and high latitudes in winter are a factor of two to three larger than the mean values of the predicted decreases. This finding suggested that the observed ozone changes may be due, in part, to the increased atmospheric abundances of the CFCs.

Subsequent to the OTP, the results from five new reanalyses of the same OTP data set by three independent analyses, using a variety of statistical models and assumptions, were generally consistent with the earlier result. Zonal mean ozone decreases derived for winter lie in the range 3.2 to 4.0% over 17 years, when averaged over the latitudes 30 to 64°N, compared to the value of 4.4% from the OTP analysis. The conclusions were found to be insensitive to the representations used for the QBO and solar cycle, strengthening the belief that the observed trends cannot be attributed to known natural processes.

The extension of the data set beyond that used by the OTP to include 1987 and 1988 does not alter the basic conclusions regarding trends in winter. In addition, no statistically significant zonal trends were found for the summer period (May - August) through 1988. Lastly, within longitudinal sectors, regional differences in the ozone trends were indicated in the Northern Hemisphere, i.e., with the largest changes being observed over North America and Europe and the smallest over Japan.

The present Dobson network and data are inadequate to determine total column ozone changes in the Arctic, tropics, subtropics, or Southern Hemisphere outside of Antarctica. Satellite data can provide the desired global coverage, but the current record is too short to differentiate the effects of natural and human-influenced processes on ozone.

- *Substantial uncertainties remain in defining changes in the vertical distribution of ozone.*

Since the chlorine/ozone theory had predicted that the greatest percentage ozone depletion should occur near 40 km altitude, the OTP looked for indications of such changes in a variety of reanalyzed data sets. The Panel reported that, based on the SAGE satellite data averaged over 20 to 50°N and S latitudes, ozone near 40 km had decreased by 3 ± 2% between February 1979-November 1981 and October 1984-September 1987. The SAGE data also indicated a percentage decrease in ozone near 25 km that is comparable in magnitude to that at 40 km. Furthermore, the Panel reported that, based on the Umkehr data from five northern mid-latitude stations, the ozone between 38 and 43 km had decreased by 9 ± 4 % between 1979 and 1986, but this uncertainty range did not account for possible systematic errors. Because the SAGE and Umkehr data records were so short (i.e., less than one solar cycle), no attempt was made to distinguish between solar-induced and human-influenced contributions to these changes.

Adding 15 months of new SAGE data does not change the picture appreciably. Again, no attempt was made to separate the contributions from natural and human-influenced processes. Additionally, a more thorough analysis of data from 10 Umkehr stations in the Northern Hemisphere for the period 1977 to 1987 reports a statistically significant decrease in ozone between 30 and 43 km. The decrease near 40 km being 4.8 ± 3.1%, after allowing for seasonal and solar-cycle effects and correcting the data for aerosol interferences. These losses are somewhat less than those predicted by the chlorine/ozone theory.

Based on SAGE, Umkehr, and ozonesonde data, there are continuing indications of a stratospheric ozone decrease at 25 km and below. Changes at these altitudes are not predicted by global models based only on gas-phase processes. It is not clear whether this points to missing processes in the models or that these sparse measurements are not representative of the global atmosphere. However, such changes are qualitatively consistent with those required for compatibility with the total column measurements.

- *Recent measurements suggest that the rate of growth in atmospheric methane has slowed somewhat.*

It would appear that the rate of methane increase has been slowing down over the last decade, namely, from 16 to 20 ppbv per year in the early 1980s to 12 to 16 ppbv per year in the late 1980s. For the other trace gases that influence stratospheric ozone and climate (CFCs, nitrous oxide, and carbon dioxide), the observed rates of increase have not changed significantly since the time of the OTP report.

Theoretical Predictions

- *Theoretical models do explain many of the general features of the atmosphere, but new limitations have been recognized.*

Many processes control the distribution of trace gases in the atmosphere. To adequately simulate the atmosphere, models must include representations of numerous radiative, chemical, and small- and large-scale dynamical processes. Current models do indeed reproduce many of the patterns observed, for example, in the ozone column: a minimum in the tropics and maxima at high latitudes in the spring of both hemispheres. Furthermore, the north - south and vertical distributions of the ozone concentration are in general agreement with satellite observations, except for Antarctica. On the other hand, a long-standing discrepancy has been the systematic underestimation of ozone concentrations near 40 km.

Several major shortcomings have been identified recently. None of the assessment models adequately represent polar meteorology or attempt to include heterogeneous processes, i.e., chemical reactions on PSCs. The failure to include these processes would likely lead to an underprediction of ozone loss, both directly at polar latitudes and possibly indirectly at midlatitudes due to dilution arising from large polar ozone losses.

Furthermore, only a few models include the influence of increasing carbon dioxide abundances and decreasing ozone abundances on temperature, which, in turn, leads to a decrease in the destruction of ozone through lower temperatures in the stratosphere. Hence, while there are still open questions regarding the quantitative treatment of the influence of CO_2 (temperature feedback), the predicted ozone depletions from chlorine- and bromine-containing chemicals are less for those global assessment models used in this report (gas-phase chemistry only) that account for CO_2 increases than the predicted ozone depletions from those models that keep temperatures fixed.

Current understanding predicts that, if substantial emissions of halocarbons continue, the atmospheric abundances of chlorine and bromine will increase and, as a result, significant ozone decreases, even outside of Antarctica, are highly likely in the future.

Several scenarios, which represent a spectrum of possible choices regarding man-made emissions of chlorine- and bromine-containing chemicals, have been used to examine the response of stratospheric ozone to atmospheric chlorine and bromine abundances. The predictions for the year 2060 relative to the year 1980 are discussed below for some of those scenarios. In each scenario, it was assumed that the recent trends continue in the atmospheric abundances of methane, nitrous oxide, and carbon dioxide of 15 ppbv, 0.25%, and 0.4% per year, respectively. The scenarios examined and the results predicted are the following:

SCENARIO (1) A freeze of CFCs 11, 12, 113, 114, 115, halons 1211, 1301 and 2402 at 1985 production levels; CCl_4, CH_3CCl_3, Hydrochlorofluorocarbon (HCFC) 22 abundances increase at approximately 1 part per trillion by volume (pptv) (1% of today's level), 4 pptv (3% of today's level), and 6 pptv (7.5% of today's level) per year, respectively.

The chlorine loading of the atmosphere is predicted to reach 9.2 ppbv by the year 2060, about three times today's level, and the bromine loading 31 pptv, about two and one half times today's level . For models that did not include the effect of carbon dioxide (i.e., temperature feedback), predicted column ozone reductions were 1 to 4% in the tropics, and from 8 to 12% at high latitudes in late winter. For models that did include the effect of carbon dioxide, predicted column ozone reductions were 0 to 1.5% in the tropics and from 4 to 8% at high latitudes in late winter. These predictions do not include the effects of heterogeneous processes, which would increase the predicted ozone depletions, at least in polar regions. Ozone is predicted to decrease by 35-50% at 40 km in models with no temperature feedback, and about 25-40% in models with temperature feedback, and results in stratospheric temperature decreases of 10 to 20 K.

SCENARIO (2) A 50% cut in emissions of CFCs 11, 12, 113, 114, 115, halons 1211, 1301 and 2402 from 1985 production levels by the year 2000; CCl_4, CH_3CCl_3, HCFC 22 increase at approximately 1 pptv, 4 pptv, and 6 pptv per year, respectively, plus a 50% substitution of CFC reductions augmenting HCFC 22 fluxes (used as a surrogate for other HCFCs).

The chlorine loading of the atmosphere is predicted to reach 7.2 ppbv by the year 2060, and the bromine loading 22 pptv. Only models that did not include the effect of carbon dioxide were used to calculate ozone depletions for this scenario. Predicted column ozone reductions were 1.5 to 3.0% in the tropics, and from 5 to 8% at high latitudes in late winter. These predictions do not include the effects of heterogeneous processes, which would increase the predicted ozone depletions, at least in polar regions. Ozone is predicted to decrease by 25-40% at 40 km (without temperature feedback). Temperature feedbacks are expected to reduce the predicted ozone depletions as in scenario 1.

SCENARIO (3) A 95% cut in emissions of CFCs 11, 12, 113, 114, 115, halons 1211, 1301 and 2402 from 1985 production levels by the year 2000; CCl_4, CH_3CCl_3, HCFC 22 increase at approximately 1 pptv, 4 pptv, and 6 pptv per year, respectively, plus a 50% substitution of CFC reductions augmenting HCFC 22 fluxes.

The chlorine loading of the atmosphere is predicted to reach 5.4 ppbv by the year 2060 and the bromine loading 14 pptv. For models that did not include the effect of carbon dioxide, there was little change in column ozone in the tropics, and a decrease from 2 to 4%

at mid-latitudes. For the one model that did include the effect of carbon dioxide, column ozone was predicted to increase by 0 to 2% at most latitudes. These predictions do not include the effects of heterogeneous processes, which would increase the predicted ozone depletions, at least in polar regions. Ozone is predicted to decrease by 20-30% at 40 km.

SCENARIO (4) 95% cut in emissions of CFCs 11, 12, 113, 114, 115; halons 1211, 1301, 2402; freeze of CCl_4 and CH_3CCl_3 atmospheric levels constant at 1985; HCFC 22 increase at approximately 6 pptv per year, but no substitution of CFCs with HCFC 22.

The chlorine loading of the atmosphere is predicted to be about 3.6 ppbv by the year 2060, comparable to that of today, and the bromine loading 14 pptv. One model that did not include the effect of carbon dioxide predicted little change of ozone in the tropics and a decrease of up to to 4% at high latitudes. These predictions do not include the effects of heterogeneous processes, which would increase the predicted ozone depletions, at least in polar regions.

SCENARIO (5) 100% cut in emissions of CFCs 11, 12, 113, 114, 115; halons 1211, 1301, 2402; and CCl_4, CH_3CCl_3, and HCFC 22 by the year 2000.

This calculation was performed to examine the chlorine loading of the atmosphere with time. By the year 2060, the chlorine loading is predicted to be about 1.9 ppbv, significantly less than that of today and approximately the level required to return the Antarctic ozone layer to levels approaching its natural state, assuming that current meteorological conditions continue. Although no model calculations were performed using this scenario, it is likely that all models would predict an increase in global ozone due to the effects of carbon dioxide and methane.

Halocarbon Ozone Depletion and Global Warming Potentials (ODPs and GWPs)

- *The impact on stratospheric ozone of the halocarbons (HCFCs and HFCs) that are proposed as substitutes for the CFCs depends upon their chemical removal processes in the lower atmosphere (troposphere).*

Because they contain hydrogen atoms, the HCFCs and HFCs are primarily removed in the troposphere by reaction with the hydroxyl radicals (OH). Although the photochemical theory of tropospheric OH is well developed, it has not been validated experimentally, and the global OH distributions are based on models. Furthermore, the global abundance of OH is influenced by tropospheric composition, which is changing.

The various estimates of the lifetimes of HCFCs and HFCs in the troposphere have an uncertainty of ± 50%. This contributes an important source of uncertainty in the prediction of the ODPs and GWPs of the HCFCs and HFCs. The fate of the degradation products of the HCFCs and HFCs and their environmental consequences are inferred from data on analogous compounds and hence the specific degradation processes require further study.

- *The values of the ODPs for the HCFCs are significantly lower than those for the CFCs.*

Theoretical predictions performed by different groups using a variety of models have calculated similar, but not identical, values for the ODPs of the HCFCs, as indicated in Table 1 below.

None of the models used for calculating the ODPs are able to simulate the chemical and dynamical processes causing the Antarctic ozone hole. However, relative to CFC 11, the local Antarctic ODPs of HCFCs 22, 142b, and 124 will be larger, perhaps as much as a factor of two or three times greater than those derived from model calculations that do not include heterogeneous chemistry and that cannot simulate polar dynamical processes. The ramifications of polar ozone depletion for ODPs is not currently clear.

The HCFCs all have much larger relative ozone depletion potentials during the first 30 to 50 years after their emission into the atmosphere compared to their steady-state ODP values. The transient values depend upon the atmospheric lifetime and their transport time to the region of destruction of the gas. This transient affect is implicitly taken into account by all models calculating atmospheric chlorine abundances and ozone depletion.

- *The steady state values of the halocarbon GWPs of the HCFCs and HFCs are lower than those of the CFCs.*

The key factors that establish the halocarbon GWP of a HCFC or HFC are its lifetime in the troposphere and its ability to absorb atmospheric infrared radiation. Halocarbon GWP values differ between species due primarily to differences in their lifetimes, since their abilities to absorb infrared radiation are similar. Hence, one of the the largest sources of uncertainty in the calculation of the halocarbon GWPs of the HCFCs and HFCs is quantifying their rate of removal in the troposphere. Calculations by three groups using different models for the halocarbon GWPs of the CFCs, HCFCs, and HFCs yield similar, but not identical, values, as indicated in Table 1.

The HCFCs all have much larger relative global warming potentials during the first 30 to 50 years after their emission into the atmosphere compared to their steady-state halocarbon GWP values.

Table 1. Range of Ozone Depletion Potentials (ODPs) and halocarbon Global Warming Potentials (GWPs) determined by one-dimensional and two-dimensional models, assuming scaling for HCFC ODPs and GWPs by CH_3CCl_3 derived lifetime (6.3 years).

	ODPs		GWP
Species	1-D Models	2-D Models	1-D Models
CFC-11	1.0	1.0	1.0
CFC-12	0.9 - 1.0	0.9	2.8 - 3.4
CFC-113	0.8 - 0.9	0.8 - 0.9	1.3 - 1.4
CFC-114	0.6 - 0.8	0.6 - 0.8	3.7 - 4.1
CFC-115	0.4 - 0.5	0.3 - 0.4	7.4 - 7.6
HCFC-22	0.04 - 0.05	0.04 - 0.06	0.32 - 0.37
HCFC-123	0.013 - 0.016	0.013 - 0.022	0.017 - 0.020
HCFC-124	0.016 - 0.018	0.018 - 0.024	0.092 - 0.10
HFC-125	0	0	0.51 - 0.65
HFC-134a	0	0	0.24 - 0.29
HCFC-141b	0.07 - 0.08	0.09 - 0.11	0.084 - 0.097
HCFC-142b	0.05 - 0.06	0.05 - 0.06	0.34 - 0.39
HFC-143a	0	0	0.72 - 0.76
HFC-152a	0	0	0.026 - 0.033
CCl_4	1.0 - 1.2	1.0 - 1.2	0.34 - 0.35
CH_3CCl_3	0.10 - 0.12	0.13 - 0.16	0.022 - 0.026

3. Implications

The findings and conclusions from the intensive and extensive ozone research over the past few years have several major implications as input to public policy regarding restrictions on man-made substances that lead to stratospheric ozone depletion:

- The scientific basis for the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer was the theoretical prediction that, should ~~CFC and~~ halon abundances continue to grow, there would eventually be substantial ozone depletion. *The research of the last few years has demonstrated that actual ozone loss due to the CFCs has already occurred, i.e., the Antarctic ozone hole.*

- Even if the control measures of the Montreal Protocol were to be implemented by all nations, today's atmospheric abundance of chlorine (about 3 ppbv) will at least double to triple during the next century. *Assuming that the atmospheric abundance of chlorine reaches about 9 ppbv by 2060, ozone depletions of 0 - 4% ozone in the tropics and 4 - 12% at high latitudes would be predicted, even without including the effects of heterogeneous processes.*

- The heterogeneous, PSC-induced chemical reactions that cause the ozone depletion in Antarctica and that also occur in the Arctic represent additional ozone-depleting processes that were not included in the stratospheric ozone assessment models on which the Montreal Protocol was based. Recent laboratory studies suggest that similar reactions involving chlorine compounds may occur on sulfate particles present at lower latitudes, which could be particularly important immediately after a volcanic eruption. *Hence, even with the Montreal Protocol, future global ozone depletions could well be larger than originally predicted.*

- Large-scale ozone depletions in Antarctica appeared to have started in the late 1970s and were initiated by atmospheric chlorine abundances of about 1.5 - 2 ppbv, compared to today's level of about 3 ppbv. *To return the Antarctic ozone layer to levels approaching its natural state, and hence to avoid the possible ozone dilution effect that the Antarctic ozone hole could have at other latitudes, one of a limited number of approaches is a complete phase out of all fully halogenated CFCs, halons, carbon tetrachloride, and methyl chloroform, as well as careful considerations of the HCFC substitutes. Otherwise, the Antarctic ozone "hole" is expected to remain, provided the present meteorological conditions continue.*

III. SCIENTIFIC SUMMARIES

Chapter 1. Polar Ozone

1.1 Polar Ozone Trends

The observation of substantial springtime reductions in Antarctic ozone, the Antarctic ozone "hole," focused world attention on the polar regions. In the few years since the discovery of this phenomenon, a great deal of field and laboratory data have been gathered. Theoretical studies have kept pace with the experimental investigations. This chapter provides a detailed review of the current understanding of the science of polar ozone depletion.

Differences in atmospheric dynamics of the hemispheres cause naturally lower ozone abundances in the Antarctic early spring as compared with the Arctic which should not be confused with the Antarctic ozone hole. Planetary waves are generally weaker in the Southern Hemisphere than in the Northern Hemisphere. The Southern Hemisphere polar winter stratosphere is colder and the westerly vortex is stronger and more persistent than in the Northern Hemisphere. These factors strongly influence the seasonal and latitudinal variations in ozone in the two hemispheres. The ozone hole is identified not merely with the difference in ozone abundances between the hemispheres nor with the latitude gradients, but with a decrease in the ozone abundances found in September and October over the past decade. It is now clear that these decadal trends result from a dramatic drop in total ozone that occurs each September. This unexpected ozone removal results in about a 50% decrease in column abundance by the end of September in recent years, as demonstrated by ground-based measurements from Halley Bay, Syowa, and the South Pole. Ozonesonde and satellite data reveal comparable total column changes, and show that the decreases occur primarily in the height region from about 12 to 24 km, the heart of the polar ozone layer. Further, the satellites demonstrate that the ozone hole extends over broad horizontal scales, at times covering the entire Antarctic continent.

Observed ozone trends in the warmer, winter Northern Hemisphere stratosphere are far smaller than those of Antarctica. Recent analyses suggest that the sub-polar column ozone decreases are largest in the winter and spring, on the order of 5% over the period from 1969 to 1988.

The trend in Antarctic ozone has not been monotonic, but this is not surprising. Inter-annual variations in total ozone occur at all latitudes. One cause of inter-annual variability is the Quasi-Biennial Oscillation (QBO), which is a natural fluctuation of equatorial stratospheric zonal winds and circulation. The mechanisms connecting polar latitude phenomena with the tropical QBO wind oscillation are not well understood.

1.2 Polar Stratospheric Chemistry

Hypotheses to explain the ozone hole included halocarbon chemistry, nitrogen chemistry associated with the solar cycle, and dynamical effects. Observations have ruled out the dynamical and solar cycle theories, while a broad range of measurements have been shown to be consistent with the general concepts of the halocarbon theory. The halocarbon theory is based on observations of the widespread occurrence of polar stratospheric clouds (PSCs) in the extremely cold Antarctic lower stratosphere. These provide surfaces on which heterogeneous chemical reactions can take place.

Satellite data from 1978 to the present provide information regarding the vertical, geographical and seasonal extent of the PSCs. Their frequency in the Antarctic stratosphere is about 10 to 100 times greater than in the Arctic. There is an apparent QBO variation in the occurrence of PSCs during both September and October, as well as increasing numbers of PSC sightings during the Octobers of 1985 and 1987 (years of westerly QBO phase). PSCs may also influence the radiative budget of the polar lower stratosphere, hence affecting the mean circulation and ozone distributions.

Laboratory studies suggest that some PSCs are composed of nitric acid and water, condensing at temperatures considerably warmer than the frost point. As the stratosphere cools, these will be the first type of clouds to form, while water ice clouds will form only at colder temperatures. Field studies have demonstrated that the former contain a substantial amount of nitrate. Laboratory studies have also shown that reactions involving nitrogen oxides and relatively long-lived chlorine species (such as $ClONO_2$ and HCl) can occur on cloud surfaces. These reactions convert relatively inert chlorine reservoirs to reactive species that photolyze readily, releasing chlorine free radicals which can then destroy ozone. The reactions also tie up nitrogen oxides in the long-lived species, HNO_3, thereby slowing the reformation of chlorine reservoirs such as $ClONO_2$. This maintains elevated abundances of chlorine free radicals and the associated rapid ozone destruction over notably longer periods than would be possible if the heterogeneous reactions affected only the composition of chlorine species. Both sunlight and extremely cold temperatures are necessary for accelerated ozone loss.

Once liberated, the chlorine rapidly forms chlorine monoxide (ClO), which can then participate in several ozone-destroying catalytic cycles. These involve formation of the dimer of chlorine monoxide as well as reactions of ClO with bromine monoxide (BrO), hydroperoxyl radicals, and atomic oxygen. Laboratory studies have provided most of the rate coefficients and photochemical parameters needed to characterize these cycles, although there are still significant uncertainties in both homogeneous and heterogeneous chemistry.

1.3 Field Observations

Observations of ClO and BrO in Antarctica have provided a critical test of the halocarbon theory of ozone depletion. In situ and remote measurements using two independent techniques have demonstrated that the ClO abundances near 20 km are typically about 1 ppbv in the Antarctic vortex during September, about one hundred times greater than theoretical predictions that do not include heterogeneous chemistry. However, these elevated ClO abundances are broadly consistent with modeling studies considering the likely PSC chemistry, frequency and duration. While there are differences in detail among these studies, all show that a substantial fraction of the observed ozone loss (60 to 100%) can be explained by the observed ClO and BrO abundances using current measurements of kinetic rates. The Antarctic ozone loss is at present believed to be dominated by the dimer cycle during years when depletion is largest, with bromine reactions contributing about 15 to 35% and reactive hydrogen contributing about 10 to 15% to the total chemical loss rate. During years of lower Antarctic ozone depletion (e.g., 1988) and in the Arctic, the bromine chemistry is calculated to be more important. Uncertainties in measurements, model formulation and the potential importance of transport processes currently preclude a fully quantitative evaluation of the consistency between observed rates of ozone change and photochemical mechanisms.

A broad range of ancillary measurements in Antarctica supports and extends our confidence in the understanding of changes in gas-phase composition caused by PSCs. These include: in situ measurements of H_2O, NO_y (total reactive nitrogen), NO, particle sizes, and particulate nitrate, as well as long-path measurements of OClO, HCl, HF, $ClONO_2$, NO_2 and HNO_3. Of particular importance are the observations of NO_y and H_2O, which show extensive denitrification and dehydration in the Antarctic vortex, believed to result from sedimentation of cloud particles.

Denitrification is of particular importance since it controls the amount of nitrogen oxides remaining after PSCs have disappeared, and hence, as mentioned earlier, may strongly affect the rate of reformation of chlorine reservoirs.

Similar chemical measurements have been obtained in the Arctic stratosphere. Satellite and ground-based measurements of steep latitudinal gradients in Arctic NO_2 abundances (the Noxon "cliff") suggest the presence of mechanisms depleting NO_2 in north polar regions. The decrease in NO_2 is qualitatively related to increases in HNO_3 abundances, indicating mechanisms for nitrogen oxides suppression without denitrification (different from that observed in Antarctica). Such an increase could occur, for example, through heterogeneous reactions followed by cloud evaporation. Concentrations of ClO as high as 1 ppbv were observed inside the Arctic polar vortex in the winter of 1989. Enhanced column abundances of $ClONO_2$ and reduced abundances of HCl and NO_2 also indicated the importance of heterogeneous chemistry similar to that of Antarctica. No unambiguous evidence for ozone loss has yet been identified for the winter of 1989. Readily detectable ozone reductions would be expected to occur only if high concentrations of ClO were maintained for sufficiently long periods in cold, illuminated air. Vortex dynamics during the 1989 winter probably limited these conditions, and are likely to do so in most Northern Hemisphere winter/spring seasons. Thus the Northern Hemisphere ozone trends cannot be unambiguously identified with PSC chemistry, although the observations are qualitatively consistent with such an explanation.

1.4 Dynamics

The role of dynamical coupling has been examined in many different studies. Synoptic scale disturbances (tropospheric weather systems) can affect total ozone amounts locally, and may lead to the formation of PSCs. Air may flow through such systems and become chemically perturbed. If there is significant flow of air into and out of the stratospheric polar vortex, ozone amounts may be reduced well outside of the region where heterogeneous chemical reactions on PSCs can occur. Further, some PSCs may be found outside of the denitrified and dehydrated region and may induce chemical perturbations at sub-polar latitudes during winter. Quantitative details are uncertain. Export of air that has undergone ozone depletion may dilute ozone concentrations at lower latitudes when the polar vortex breaks down in the spring. Numerical models indicate that about a 2% change might occur in ozone amounts at mid-latitudes of the Southern Hemisphere due to dilution, and suggest that some fraction of the dilution may remain from one year to the next.

Measurements of the vertical profiles of long-lived tracers such as N_2O and the chlorofluorocarbons in the polar vortices reveal low values compared to those at other latitudes. These apparently result from downward motion and have important implications not only for representations of vortex dynamics but also for chlorine chemical perturbations. For example, measurements indicate only about 0.3 ppbv of total chlorine in the form of chlorofluorocarbons near 20 km at 70°S as compared to 1.0 ppbv at 45°S in about 1987; these imply that the corresponding abundances of reactive chlorine are on the order of 2.2 and 1.5 ppbv, respectively. Thus, the amount of reactive chlorine available for reactions on PSC surfaces in the polar regions is likely to be significantly enhanced compared to lower latitudes.

The stratospheric circulation exhibits variability on a range of time scales. In particular, there is substantial inter-annual variability in the two hemispheres, especially in the Northern Hemisphere. A very deep ozone hole occurred over Antarctica in spring, 1987. The hole was not as deep in 1988, perhaps because dynamics and transport were more vigorous in 1988 than in 1987. Temperatures were also warmer during September 1988 as compared to 1987, which is likely to be the primary cause for a corresponding decrease in PSC cloud frequencies in the regions sampled by the SAM II satellite between the two years. These factors may yield important differences in heterogeneous chemical perturbations and hence may explain qualitatively the difference in the depth of the ozone hole obtained (with 1988 being much less depleted than 1987). The observed behavior fits general expectations based on QBO behavior since the equatorial winds were strongly westerly near 25 km during October 1987, whereas 1988 was characterized by a transition from westerly to easterly winds. If the current QBO cycle has the average period of about 28 months, winds will remain easterly through October 1989, but change to westerly before September 1990. If the past correlation between the QBO and the ozone hole continues and if the current QBO cycle exhibits a period close to the average, then the ozone depletion should be expected to be relatively modest in 1989 and quite deep in 1990 (note, however, that the QBO period can vary by as much as 8 months so that the measured equatorial winds must be examined before any firm comparisons can be made). The next few years should therefore provide an excellent test of the relationship between the QBO and the Antarctic ozone hole.

Minimum temperatures in the high latitude Northern Hemisphere stratosphere were unusually low in late-January/early-February, 1989. PSCs were observed as far equatorward as 50ºN. A strong, dynamically induced warming occurred at polar latitudes in mid-February and temperatures rose above the threshold values required for PSC formation. Poleward transport of air rich in ozone and nitrogen oxides is likely to have occurred. This warming of the Arctic vortex probably played an important role in limiting ozone loss during 1989.

On the basis of radiosondes and satellite data, a downward trend in lower stratospheric temperatures has been deduced at high southern latitudes from 1979 through 1987 (note, however, that in 1988 temperatures were much warmer than they would have been if this trend had continued monotonically). The largest changes, about 1K/year, were found in the means for October and for November, while no trend was found in September, when most of the Antarctic ozone loss is observed. The observed time lag between the temperature change and the ozone loss, as well as radiative studies with 1-D, 2-D, and 3-D models suggest that the temperature trend is the result of the ozone trend rather than its cause (i.e., reduced ozone abundances are predicted to yield smaller solar ultraviolet heating rates and hence colder temperatures).

1.5 Future of Polar Ozone

The future depletion of polar ozone depends in large part on mankind's use of halocarbons, although other factors may also contribute. In contrast to its behavior at ground level, increased concentrations of carbon dioxide may cool the stratosphere, perhaps affecting the duration and spatial extent of the PSCs in both hemispheres. Possible changes in climate and in the concentrations of atmospheric methane and nitrous oxide may also affect the processes related to the Antarctic ozone hole. The bulk of the chlorine currently in the stratosphere comes from chlorofluorocarbons that have atmospheric removal times on the order of 50 to 100 years, and hence the ozone hole will likely remain over Antarctica for many decades, even if all production were immediately halted. An examination of the Antarctic springtime column ozone record at several locations permits a rough estimate of the atmospheric chlorine content when the Antarctic ozone hole first became apparent. Assuming no changes in temperature, atmospheric dynamics, or photochemical processes, this provides an indication of the total chlorine abundances required to return the Antarctic ozone layer to levels approaching its natural state. A preliminary analysis of trace gas samples indicates an average age of polar lower stratospheric air of about five years. Coupled with the onset of detectable ozone reductions in the late 1970s, this suggests that organic chlorine mixing ratios of roughly the mid-1970s are necessary (corresponding to tropospheric total chlorine mixing ratios of about 1.5-2.0 ppbv, including the 0.6-0.7 ppbv of methyl chloride, which is believed to be of natural origin).

Chapter 2. Global Trends

2.1 Introduction

This chapter largely builds upon the Ozone Trends Panel report by adding new analyses and updating the database.

Since the 1920s, numerous techniques have been developed and applied to determine total ozone and its vertical distribution. Initially, these measurements were not made for the purpose of determining long-term trends. Fortunately, some of these systems, and only the Dobson spectrophotometer for the last 30 years, have the requisite stability to provide data from which such changes may be detected and quantitatively measured.

For trend determination, short-term random noise is not usually a significant factor, since large amounts of data are averaged. The most important characteristic is stability, i.e. the absence of time-dependent systematic errors. Accuracy is desirable, but continuing systematic errors will not obscure the detection of change.

Determination of the global trends in stratospheric ozone have been based on complementary measurements, from the ground and from satellites. Ground-based instruments can be checked and recalibrated as necessary; they are regarded as capable of long-term stable operation, although this depends on some non-technical factors. Their disadvantages are that they are local systems, and provide few observations in oceanic or remote areas. Satellite-borne instruments obtain global data, but, once launched, are not available to checking and are subject to drift. It is thus desirable to have these complementary measurements to provide checks on each other.

2.2 Trends in Total Ozone

Existing data on total ozone relies heavily on the Dobson instruments and M83/M124 instruments in the Northern Hemisphere mid-latitudes (30-64°N) so that trends can only be determined in this latitude range. Dobson instruments are referenced to the World Standard instrument, whose calibration is reported to have been maintained within ± 0.5% over the past 15 years.

Satellite data are provided by the TOMS/SBUV instruments. They have proven to be very useful to verify consistency and identify erroneous readings in ground-based instruments and to confirm the reliability of the World Standard instrument. An important recent result is the development of a method for using the TOMS/SBUV data themselves to remove the effects of long-term instrumental drift. Although such new data are not used in the following analysis, results of initial testing suggest this has been successful, and that the TOMS data can provide in the future a second, independent source of data on global trends.

The main conclusions of the study of total ozone trends are as follows (± 2 standard error limits are shown):

- *New analyses of the total ozone data set used by OTP produces negative trends whose latitudinal and seasonal patterns are consistent with the earlier results (over the 17-year period from December 1969 through 1986).*

Zonal mean decadal changes derived using various statistical assumptions lie in the following ranges during winter (December-March): for 30-39°N or 35°N, -0.9 ± 0.9% to -1.7 ± 0.9%; for 40-52°N or 45°N, -2.0 ± 0.8% to -3.0 ± 1.7%; and for 53-64°N or 55°N, -2.5 ± 1.9% to -3.7 ± 1.8%. Analogous changes during summer (May-August) are: for 30-39°N, -0.4 ± 0.9% to -1.1 ± 0.9%; for 40-52°N, -0.7 ± 0.6% to -1.1 ± 0.8%, and for 53-64°N, -0.1 ± 0.9% to -0.7 ± 0.9%. Results of an independent study performed in the USSR lie within the ranges quoted above.

- *The trends are sensitive to data obtained after October 1982 during periods of anomalies in the ozone patterns.*

If the data are analyzed up to and including October 1982, the summertime trend moves closer to zero by 0.8 to 1.0% per decade. Depending on the details of the statistical model, the analogous change in the wintertime trend is 0.3 to 0.9% per decade less negative.

- *Derived trends for the 17-year period between 1969 and 1986 are insensitive to the statistical treatment of the quasibiennial oscillation and solar cycle relationships.*

Since the Dobson ozone record approaches 30 years, the trend estimates should be nearly independent of the 11-year solar cycle effect as represented by the F10.7-cm solar flux and the quasi-biennial effect represented by equatorial 50 hPa winds. This is important in that the derived long-term trends are robust to these known natural causes of ozone variability.

- *Extension of the data set into 1988 does not alter the nature of conclusions based on measurements through 1986, although differences in detail exist.*

During winter, derived statistically significant trends are -1.8 ± 1.1%/decade, -2.3 ± 0.9%/decade, and -2.7 ± 1.2%/decade at latitudes 35°N, 45°N, and 55°N respectively. Trends derived for summer at 35°N, 45°N, and 55°N are -0.5 ± 1.1%/decade, -0.3 ± 1.0%/decade, and -0.2 ± 1.2%/decade, respectively. None of the summertime trends are statistically significant.

- *Analyses of Dobson measurements from different geographic regions reveal differences in trends.*

Over the period 1969 to 1988, European and North American stations indicate statistically significant wintertime trends of -2.9 ± 0.7%/decade. Japanese stations indicate a non-significant wintertime trend of -0.6 ± 1.0% per decade. Summertime trends vary from -1.2 ± 0.7% per decade over North America to +0.8 ± 1.2% per decade over Japan.

- *The regional differences in trends derived from the Dobson network are consistent with geographic patterns of ozone change contained in the TOMS/SBUV data sets.*

Data sets now available from satellites are useful in identifying geographic patterns in total ozone changes. However, present satellite data sets have insufficient length for definitive studies of long-term trends.

- *The observed total ozone trends for the winter are more negative than model predictions for the period 1969 through 1986 although there is close agreement between observation and prediction in the summer.*

The observed winter total ozone trends over the latitudes 30° to 60°N ranged from -1.9 ± 0.7% per decade -2.6 ± 1.2% per decade among the study groups. Based on the observed trend uncertainty limits, these changes exceed the theoretical model calculated winter changes of -0.5 to -1.2% per decade given in the OTP report. The observed summer trends ranged from -0.6 ± 0.6% per decade to -0.8 ± 0.6% per decade and were consistent within the uncertainty limits with the summer theoretical model calculations of -0.3 to-0.6% per decade.

2.3 Trends in Ozone Vertical Distribution

The situation with regard to measurements of the vertical distribution is less satisfactory. Presently, most ground-based observations have been of the Umkehr type, with extensive records at only about 10 stations, distributed very non-uniformly over the globe. The observations have a vertical resolution of 11 to 15 km, and are subject to aerosol interference, which can now be corrected for by physical-theoretical methods. The only reliable satellite data are obtained by the SAGE instruments above 25 km. It uses a ratio technique which renders the measurement insensitive to drift. The sampling is 900 profiles a month (two per orbit) with time varying non-uniform geographical distribution.

The emphasis in the current analysis is first given to the altitude range in the upper stratosphere where the percentage change in ozone concentrations at mid-latitude due to anthropogenic chlorine perturbations is expected to be the largest. The major problem for such an analysis is the scarcity in time and space of the available data base for both satellite and ground-based measurements which precludes any true global evaluation of trends in ozone vertical distributions.

- *Over the regions of maximum density of coincidences (SAGE II minus SAGE I), i.e. 20-50°N and 20-50°S, the comparisons indicate for a 6 years average time period (1980-1986):*
    - *an ozone decrease between 35 and 44 km with the maximum ozone change of -3 ± 2% occuring at 40 km.*
    - *an ozone decrease of -3 ± 2% at 25 km and an essentially zero ozone change at 28-33 km and at 45-48 km.*

The only satellite observations that can be used currently for the determination of upper-stratospheric ozone changes are based on the comparison of 33 months (1979-1981) of SAGE I and 3 years (October 1984-December 1988) of SAGE II operations. This analysis constitutes an update of the OTP report by including two more years of SAGE II data, and confirms the previous results. These values represent the changes that occur over this time period and no attempt has been made to correct for solar cycle or any other.

- *Statistically significant negative trends are observed in Umkehr layers 6-7-8 (30-43 km) that corresponds to an average ozone change of -0.4% ± 0.3 per year at 40 km.*

A trend analysis of Umkehr observations performed at 10 stations in the Northern Hemisphere for the period 1977-1987 has been made on a station-by-station basis using an autoregressive statistical model which accounts for seasonal, solar-cycle and aerosol induced effects. The latter is of particular importance when considering the high aerosol load in the stratosphere during the year 1982-1983 following the El Chichon volcano eruption.

- *Within the uncertainty limits of SAGE and Umkehr trend results near 40 km, these two independent results are not inconsistent.*

  When corrected for the solar effect on ozone over 6 years, the change in ozone from SAGE observations near 40 km is estimated to be -0.2 ± 0.4% per year that is not explained by natural and instrumental variation. When compared to the Umkehr trend of -0.4 ± 0.3% per year there is no inconsistency within the margins of error.

- *In the lower stratosphere (15-24 km), the estimated change from a limited network of Northern Hemisphere ozonesonde stations is -0.5% per year ± 0.4%.*

  Analysis of ozonesonde data at nine stations (Canada, Europe, and Japan) with records extending for the three longest ones from 1966 to 1986 has been performed to detect possible trends in ozone concentrations in the lower stratosphere. This analysis leads to some differences in the results for the various stations which probably reflect the differences in the system operation and extent of the data bases as well as varying regional effects.

- *Although at the lower edge, the simulation results are within the error bars of the observed changes in the ozone vertical distributions.*

  Calculation of changes in the ozone vertical distribution have been performed in the OTP report using 2-D models for the period 1979-1985. The calculated changes decreases peak at about -6% at mid-latitudes near 40 km.

- *The ozone decrease observed by SAGE instruments and suggested by Umkehr results in the 40 km region contribute very little to explaining the Dobson year-round total ozone trend of -1.1% per decade.*

  The SAGE change of -3% ± 0.2% at 25 km over 6 years when considered together with the negative Umkehr trend in this height range and the statistically significant, but not globally representative trend of nearly -0.5% per year observed by ozonesondes between 17 and 24 km, seems to suggest that the stratosphere below 25 km is the prime contributor to the observed total ozone trend at mid-latitude.

2.4 Trends in Stratospheric Temperature

The update of the previous temperature trend report (OTP) is based on the stratospheric temperature data set already considered, and updated when possible, and the new Rayleigh lidar data. These lidar data have been compared with the SSU (Stratospheric Sounding Unit) data and the NMC (National Meteorological Center) analyses from 1981 to 1987. Substantial differences are observed, accountable in part by changes in the NOAA satellites series.

The recent finding of a statistical relationship between the stratospheric temperature, the QBO and the 11-year solar cycle has a potential implication for trend determination. The zonal asymmetry of the 11-year solar signal, clearly shown by the radiosonde data up to 30 hPa (24 km), and confirmed by the lidar and rocket data at higher altitudes, leads locally to much larger temperature dependence than the one observed on zonal or global means. Caution must be taken when using local or regional data (for T and O_3 as well) unless the data extend over a long enough period to separate trends from solar activity effects.

In the stratosphere, long-term trends can only be obtained from radiosondes at present. Satellite observations are available for less than a solar cycle:

- *In the lower stratosphere (100-30 hPa), the temperature data over the last twenty years suggest a maximum change of -0.4 K/decade at mid- and low latitudes with larger changes occuring at higher latitudes.*

- *In the upper stratosphere, the satellite data for the period (1985/1986) - (1979/1980) indicate a global temperature change of -1.5 ± 1 K. It is compatible with the -3 ±4% change in ozone concentration around 40 km as observed by SAGE instruments.*

More work is clearly needed to bring data of different sources into agreement and to understand the causes of the large spatial variability, whether or not it is related to solar activity.

2.5 Trends in Tropospheric Source Gases and Ozone

- *For most of the tropospheric trace gases, the observed rates of increase up to the end of 1987 have not changed significantly compared to those in the OTP report, which analyzed data up to the end of 1986.*

- *It would appear that the rate of methane increase has been slowing over the last decade, from 16-20 ppbv per year in the 1980s to approximately 12-16 ppbv per year in the late 1980s.*

- *Trend analysis of surface ozone measurements from ozonesonde and ground-based instruments show variable results.*

  The 16 Northern Hemispheric sites show a range of trends from -1.1 to +3.1% per year. Ten of the Northern Hemispheric sites show statistically significant positive trends, one site shows a statistically significant negative trend. The remaining sites show trends that are not significant. The seven European sites all show statistically significant positive trends, ranging from +1.1 to +3.1% per year. All four Canadian sites show negative trends, from -0.1 to -1.1% per year, only one of which is statistically significant. All three Japanese sites show positive trends, ranging from +0.9 to +2.5% per year, two of which are significant. The four Southern Hemispheric sites show trends ranging from -0.5 to +0.6% per year, only one of which is significant.

2.6 Trends in Stratospheric Aerosols

- *Stratospheric aerosols can produce artifacts in ozone measurements by remote sensing instruments and, in the case of Antarctic PSCs, have been shown to impact ozone destruction through heterogeneous chemistry. In addition, laboratory studies suggest that heterogeneous processes may occur on the surface of sulfuric acid/H_2O aerosols, which are greatly enhanced after volcanic eruptions. The latter effect could be important in providing a mechanism for ozone destruction on a global scale.*

- *From the standpoint of global trends, global stratospheric aerosol loading which peaked after the eruption of El Chichon, has generally decreased. Although low in 1989, it has not yet reached the lowest values observed in 1978-1979. The 1989 values have little or no effect on ozone measurements.*

2.7 Trends in Surface UV Radiation

The Robertson-Berger meters located in the United States showed no increase in surface ultraviolet radiation over the period 1974 through 1985. The measurements do not contradict the observed downward trend in total ozone. The meter is not sensitive to small changes in ozone, and in addition, the system is strongly influenced by cloudiness and sources of pollution.

Chapter 3. Model Predictions

3.1 Stratospheric Models

In order to estimate the impact of man-made chemicals on atmospheric ozone, it is essential to develop models that perform long-term predictions. Current models that are used for these predictions include rather detailed schemes for homogeneous chemistry and, to some extent, account for radiative and dynamical feedbacks. Two-dimensional models predict the latitudinal and seasonal changes in ozone and other trace gases. Among the available models for calculating ozone globally, these 2-D models currently include the best representation of homogeneous physical and chemical processes in the middle atmosphere and have been compared extensively with observations of many stratospheric chemical species. However, none of these models properly account for heterogeneous chemistry and polar dynamics. Because of computational requirements and development time, the recently available three-dimensional models have had only limited applications in assessment studies, but are important in resolving some issues of model formulation and dynamical feedbacks.

An important prerequisite for prediction models is that they represent with sufficient accuracy the present distributions of trace gases. The 2-D models involved in the present assessment generally reproduce the patterns observed in the ozone column, with a minimum in the tropics and maxima at high latitudes in the spring of both hemispheres. The meridional distribution of local ozone is also in good agreement with the satellite observations. However, important discrepancies have also been noted: in particular, the models systematically underestimate ozone concentrations near 40 km, where they should accurately represent the physical and chemical processes controlling ozone. Calculated and observed distributions and seasonal variations of species such as nitrous oxide, methane, nitric acid, nitrogen oxides and chlorine monoxide are in qualitative agreement, although substantial quantitative differences are found in certain cases.

The recent intercomparison of stratospheric models (1988, Virginia Beach) has highlighted many specific differences in the models, but did not yet resolve their causes. For example, the photodissociation rates were compared using specified ozone and temperature fields and found to differ among models by a factor of 2 or more in many instances. Follow-up studies examining the detailed radiative transfer in the models are continuing. Tests of the model circulation using synthetic tracers with specified chemistry has revealed substantial differences in the rate of upward motion in the tropical stratosphere. In spite of these individual differences, the calculated distribution of ozone is in good agreement between the models, and may demonstrate the robustness of the ozone photochemistry in these models.

3.2 Important Issues in Ozone Modeling

Modeling the polar regions is an especially challenging task because of the difficulty both in simulating the physics and chemistry of polar stratospheric clouds (PSCs) and in modeling the dynamical processes controlling the distribution of tracers and temperature of the high-latitude lower stratosphere in winter. The model predictions in this assessment do not include the effects of heterogeneous processes involving chlorine and nitrogen-containing chemicals on the surface of particles in PSCs. These processes are known to increase the abundance of the chlorine radical, ClO, which plays an important role in reducing ozone in the Antarctic atmosphere. In several models, exploratory studies including these effects were performed, and showed substantially enhanced ozone depletion at high latitudes during winter and smaller changes in neighboring midlatitudes for much of the year. Additional studies, including some of these 2-D models and other 3-D models, have shown that the transport of ozone-depleted air from the Antarctic region today can account for ozone reductions at mid-latitudes of several per cent.

Laboratory studies suggest that heterogeneous processes on the natural background aerosols (Junge layer, which can be perturbed by volcanic eruptions) could also contribute to enhanced chlorine-catalyzed ozone destruction over much of the globe. Several model studies have examined the effects of parameterized heterogeneous reactions on sulfuric acid aerosols and have shown the possibility for additional ozone depletion. Because of uncertainties in the laboratory data on rate constants for these reactions under stratospheric conditions, only sensitivity studies can be made at present.

Stratospheric temperature perturbations resulting from changes in CO_2 or tropospheric climate will in turn affect the photochemistry of ozone. In the upper stratosphere for the scenarios described below, increased CO_2 and reduced ozone both lead to temperature reductions near the stratopause of 10-20 K by the year 2060. This significant cooling is a robust feature of simulations; it leads to a reduced rate of ozone photochemical loss and hence moderates the ozone depletion due to chlorine. In the lower stratosphere, a particularly difficult region to model, smaller temperature changes are predicted. If the lower stratosphere cools significantly (2-4 K) in the future, then reduced chemical loss predicted by the models with homogeneous chemistry would lead to an increase in ozone concentrations that must be considered along with other perturbations. Such changes in stratospheric temperatures could be accompanied by changes in the circulation. A number of the models used in this assessment include radiative feedbacks, and some attempt to account for circulation feedbacks.

3.3 Atmospheric Scenarios and Calculated Ozone Depletion

The composition of the atmosphere will depend on the rate at which halocarbons and other trace gases will be emitted in the future. Several scenarios have been considered in this assessment in order to examine the impact of possible control policies. Their details are specified in Table 3.1. None of the individual scenarios is intended to be a prediction of the future atmospheric composition; the range is only illustrative of different strategies for halocarbon control. They are used to define a range of chlorine and bromine loadings to the atmosphere and to study the consequent response of stratospheric ozone.

The predictions given here should be interpreted with caution in the light of the models' successes and limitations discussed above. Thus, given that the broad features of the present atmosphere are in general reproduced satisfactorily, it is then the broad features of the predictions that should be given most credence. For example, predictions of ozone and temperature changes near 40 km, as well as that of global chlorine loading, are probably more robust than detailed latitudinal behavior, especially in view of the models' lack of PSC chemistry.

(1) Reference Scenario. In the reference scenario (A1), the fluxes of the CFCs (11, 12, 113, 114, 115) and halons (1211, 1301, 2402) controlled under the Montreal Protocol were held constant at their estimated 1985 production levels. The concentration of additional halocarbons and other chemically and radiatively important gases were assumed to increase at rates consistent with presently observed trends: CCl_4 at +1 pptv/yr (+1%/yr in 1985); CH_3CCl_3 at +4 pptv/yr (+3%/yr in 1985); CH_4 at +15 ppbv/yr (+0.9%/yr in 1985); N_2O at +0.25%/yr; CO_2 at +0.4%/yr. For HCFC-22 the current estimated emissions (140 Gg/yr in 1985) and growth rate in emissions (5%/yr of the 1985 emission rate) were chosen to be consistent with the limited atmospheric

Table 3.1. Scenarios for Halocarbon Abundances

(a) 1985 Conditions

Gas	Mixing Ratio (pptv)	Flux (Gg/yr)	Gas	Mixing Ratio
CFC-11	220	350	CCl_4	100 pptv
CFC-12	375	450	CH_3CCl_3	130 pptv
CFC-113	30	150	CH_3Cl	600 pptv
CFC-114	5	15	CH_3Br	10 pptv
CFC-115	4	5		
halon 1211	1.5	5	N_2O	306 ppbv
halon 1301	1.7	8	CH_4	1600 ppbv
HCFC-22	80	140	CO_2	345 ppmv

(b) Scenario Definitions

Scenario	CFC cut (1996-2000)	CFC-22 Surrogate	CFC-22 Growth	CCl_4 Growth	CH_3CCl_3 Growth
A1	0 %	---	+7 Gg/yr/yr	+1 pptv/yr	+4 pptv/yr
B1	50 %	50 %	+7 Gg/yr/yr	+1 pptv/yr	+4 pptv/yr
C1	85 %	50 %	+7 Gg/yr/yr	+1 pptv/yr	+4 pptv/yr
D1	95 %	50 %	+7 Gg/yr/yr	+1 pptv/yr	+4 pptv/yr
D2	95 %	50 %	+7 Gg/yr/yr	fix (1985)	fix (1985)
D3	95 %	0 %	+7 Gg/yr/yr	fix (1985)	fix (1985)
E1	100 %	50 %	+7 Gg/yr/yr	+1 pptv/yr	+4 pptv/yr
E2	100 %	50 %	+7 Gg/yr/yr	fix (2000)	fix (2000)
E3	100 %	50 %	+7 Gg/yr/yr	cut (2000)	fix (2000)
E4	100 %	50 %	+7 Gg/yr/yr	cut (2000)	cut (2000)
E5	100 %	0 %	+7 Gg/yr/yr	cut (2000)	cut (2000)
E6	100 %	0 %	fix (2000)	cut (2000)	cut (2000)
E7	100 %	0 %	cut (2000)	cut (2000)	cut (2000)
E8	95 %	0 %	cut (2000)	cut (2000)	cut (2000)
E9	85 %	0 %	cut (2000)	cut (2000)	cut (2000)
E10	100 %	50 % cut (2030)	cut (2030)	cut (2000)	cut (2000)

(c) Total Chlorine Abundance, Summed Over All Halocarbons (ppbv)

Year	A1	B1	C1	D1	D2	D3	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
1985	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98
2000	4.52	4.41	4.33	4.31	4.07	3.98	4.30	4.30	4.30	4.30	4.21	4.21	4.21	4.22	4.26	4.30
2030	7.09	5.93	5.12	4.89	4.17	3.66	4.77	4.29	4.09	3.52	2.98	2.84	2.58	2.72	3.01	3.38
2060	9.16	7.15	5.75	5.35	4.15	3.55	5.15	4.19	3.87	3.30	2.67	2.27	1.95	2.18	2.64	2.13
2090	10.72	8.09	6.25	5.73	4.05	3.42	5.47	4.03	3.64	3.07	2.41	1.88	1.55	1.84	2.43	1.59

observations (+6 pptv/yr in 1985). Many of the models used in the assessment had specified temperature distributions and were therefore unable to include the radiative impact on stratospheric temperatures of CO_2 increases or ozone changes.

In this reference scenario (A1), the chlorine loading of the atmosphere increases from 3.0 ppbv in 1985 to 4.5 ppbv in the year 2000, to 7.1 in the year 2030, and to 9.2 in the year 2060.The bromine loading increases from 13 pptv in 1985 (10 pptv CH_3Br; 1.5 pptv halon 1211; 1.7 pptv halon 1301) to 31 pptv in the year 2060 (10 pptv CH_3Br; 3 pptv halon 1211; 18 pptv halon 1301). For models that did not contain the carbon dioxide effect, reductions in column ozone from 1980 to 2060 ranged from 1% to 4% in the tropics and from 8% to 12% at high latitudes in late winter. For models that included the carbon dioxide effect, the corresponding ozone reductions were less: 0% to 1.5% in the tropics and 4% to 8% in high latitudes in late winter. Ozone reductions at 40 km were about 35-50% in models with no temperature feedback and about 25-40% in models with temperature feedback, resulting in temperature decreases of 10-20 K. No heterogeneous chemistry was included in these models. When methane increases are suspended in 1985, ozone column reductions are larger in all latitudes and seasons by about 3%. Methane increases lead to increases in ozone by conversion of active chlorine (Cl, ClO) into inactive chlorine (HCl) and further by contributing to the direct production of ozone by "smog chemistry" in the lower stratosphere and troposphere. Many of the differences in the model results occur in the lower stratosphere where it is more difficult to predict the impacts of radiative and chemical forcing.

(2) Scenarios with CFC Reductions. Several scenarios were considered in which emissions of CFCs and halons were reduced between 1995 and the year 2000, with 50% of the total CFC reduction augmenting the HCFC-22 budget. The increase in carbon tetrachloride and methyl chloroform are taken from the reference scenario. When CFC emissions are cut by 50% (B1), the chlorine loading in the year 2060 reaches 7.2 ppbv and the bromine loading is 22 pptv. The corresponding reductions in column ozone by 2060 are about 65% of those calculated for the reference scenario: 1-3% in the tropics and 5-8% at high latitudes in late winter for models without temperature feedback. Ozone reductions at 40 km are also less than in A1, 25-40% (without temperature feedback). No heterogeneous chemistry was included in these models.

When the CFC emissions are reduced by 85% (C1), the chlorine and bromine loadings in 2060 are 5.5 ppbv and 16 pptv, respectively. The reductions in column ozone are approximately 50% of those calculated in the reference scenario. No heterogeneous chemistry was included in these models.

When the CFC emissions are reduced by 95% (D1), the chlorine and bromine loadings in 2060 are 5.4 ppbv and 14 pptv, respectively. The reductions in column ozone at mid- to high latitudes are approximately 40 to 50% of those calculated in the reference scenario: very little change in the tropics and 2-4% at mid-latitudes for models without temperature feedback. Ozone reductions at 40 km are 20-30%. In the one model that includes the CO_2 effect, modest ozone column increases, 0-2%, are found at most latitudes. No heterogeneous chemistry was included in these models.

Further reductions in chlorine loading were considered by freezing concentrations of methyl chloroform and carbon tetrachloride (D2). When CFC emissions were also cut by 95%, the chlorine loading at 2060 was reduced to 4.2 ppbv. The reductions in column ozone were about 30% of that in the reference scenario, corresponding to about 60% of those calculated in the similar case when CCl_4 and CH_3CCl_3 were assumed to increase. If in addition, the 95% cut back in CFC emissions is not compensated for by increased emission of HCFC-22 (D3), the chlorine loading at 2060 is reduced further to 3.6 ppbv, but the calculated ozone columns are not significantly different: little change in the tropics and a decrease of up to 4% at high latitudes. This change in chlorine loading, from 4.2 to 3.6 ppbv, has little effect on column ozone because it is associated with changes in HCFC-22 abundance. In these current assessment models, HCFC-22 does not release a large fraction of its chlorine in the middle stratosphere where chlorine catalyzed loss of ozone is most important. No heterogeneous chemistry was included in these models.

(3) Examination of chlorine loading. Thus far, in all of the scenarios (A-D) the tropospheric mixing ratio of chlorine, when summed over all halocarbons (i.e., chlorine loading), is well above the 1985 levels of 3 ppbv by the end of the scenarios in 2060. It is interesting to note what different combination of halocarbon reductions could possibly yield a chlorine loading of less than 3 ppbv by 2060, and also whether chlorine levels prior to the onset of the Antarctic ozone hole (at most 2 ppbv) could be achieved by 2060 with any combination of freezes or cuts in halocarbon emissions in the year 2000. Additional scenarios (E) in the Table 3.1 explore the range of chlorine loading assuming that emissions of all halocarbons by 2000 can be completely eliminated by 2000, except for CH_3Cl. Only a complete cut in emissions of CFCs, HCFC-22, CCl_4, and CH_3CCl_3 results in chlorine loading less than 2 ppbv by 2060, although a combination of cuts and reductions in emissions (including low levels of CFC emissions) can give values below 3 ppbv. If the time frame is extended to 2090, there is a slightly greater range of emission restrictions that will result in 2 ppbv of atmospheric chlorine. Model assessments of these scenarios were not performed since the ozone perturbations would be dominated by the increases in CH_4, N_2O, and CO_2 rather than the chlorine abundances.

3.4 Changes in Ultraviolet Radiation at the Surface

The changes in UV radiation at the surface have been calculated both for the observed changes in ozone column over the past decade and for the predicted changes in the future. The ultraviolet spectrum has been averaged to account for DNA damage, for plant damage, and for the Robertson-Berger meter's response. The TOMS data normalized to Dobson was used to define the change in the column over the past decade (0 to -4% in the tropics, -4 to -8% in northern high-latitude winter, and -8 to -30% at high southern latitudes from March through December). The calculated UV doses for DNA and plant damage increased by 2-5% in the Northern Hemisphere, by 2-10% between 30°S and 60°S, and by 10-60% under the Antarctic ozone hole. Predictions for 2060 from a model with fixed temperatures and circulation, neglecting heterogeneous chemistry, were used to illustrate future ozone perturbations (reference scenario A1 yielding a chlorine loading of 9.2 ppbv in 2060, 1-4% reduction in tropical total ozone, and 8-12% reduction at high latitudes). The largest absolute increase in average UV dose for the 1960-2060 period is predicted to occur in the springtime at mid-latitudes, and values may be sensitive to systematic latitudinal differences in cloud cover. The greatest relative increase, 20-40%, occurs at high latitudes in early spring. For the scenario in which CFC emissions are cut by 95% in year 2000 (chlorine loading of 5.4 ppbv), the calculated increases in UV dose are half as large.

Chapter 4. Halocarbon Ozone Depletion and Global Warming Potentials

Concern over global environmental consequences of fully halogenated chlorofluorocarbons (CFCs) has sparked interest in the determination of the potential impacts on stratospheric ozone and climate of halocarbons, both chlorinated and brominated. In particular, the recent search for replacement compounds for the CFCs has primarily focused on several hydrogen-containing halocarbons (HCFCs, HFCs) which need to be closely examined. The kinetics and degradation mechanisms of many of these compounds (CFCs, HCFCs, HFCs, and halons) in the troposphere, their potential relative effects on stratospheric ozone, and their potential relative effects on global climate have been evaluated.

4.1 Halocarbon Oxidation in the Atmosphere

The halocarbons containing hydrogen atoms (HFCs and HCFCs), which have been proposed for substitutes for CFCs, react with the OH radical and are primarily removed in the troposphere by this process. The rate constants for attack of OH on these compounds are well defined (±20% at relevant temperatures) and this reaction is the major loss process for these molecules in the atmosphere.

There are virtually no experimental data available concerning the subsequent reactions occurring in the atmospheric degradation of HFCs and HCFCs. By analogy with similar chemical species it is predicted that the major products formed from the reactions of the OH radical with HFCs and HCFCs under tropospheric conditions are halogen substituted carbonyl compounds and hydrogen halides. Based on the available knowledge of gas phase chemistry only four of the possible products appear to be potentially significant carriers of chlorine to the stratosphere: $CClFO$, CF_3CClO, $CClF_2CO_3NO_2$ and $CCl_2FCO_3NO_2$. Physical removal processes (to the liquid phase) will probably reduce this potential, but tropospheric removal pathways for the carbonyl compounds, especially the physical processes, are not well understood and require further study.

The oxidizing efficiency of the troposphere is determined by the abundance of OH radicals. However, quantitative validation of photochemical models by direct experimental measurement of the tropospheric OH concentrations has not been satisfactorily achieved. Global budgets and distributions of methyl chloroform and ^{14}CO have been used to estimate a volume-averaged global OH concentration of 6 (± 2) x 10^5 molecule cm^{-3}. The budget and lifetime of methyl chloroform calculated using OH fields predicted by models is in general agreement with these results.

The calculated lifetimes of HFCs and HCFCs range from 0.25-40 years with an uncertainty of ± 50%. These are shorter than the lifetimes for the fully halogenated CFCs.

Ozone and ozone precursors (CH_4, CO, NO_x, and non-methane hydrocarbons) can influence OH concentrations in the troposphere and hence could indirectly influence the lifetime of halocarbons. Model calculations indicate that, if manmade emissions of ozone precursors continue to increase, ozone concentrations are anticipated to grow throughout the Northern Hemisphere. The magnitude of the predicted ozone increase will depend on the detailed assumptions made concerning future emissions of ozone precursors. Model calculations indicating future ozone increases as large as 50% also indicate future OH concentrations could decrease by as much as 25%. This would lead to increased lifetimes for many molecules removed by hydroxyl radical chemistry.

4.2 Ozone Depletion Potentials

Ozone Depletion Potentials (ODPs) have been defined as the ratio of steady-state calculated ozone column changes for each unit mass of a gas emitted into the atmosphere relative to the depletion for a mass unit emission of CFC-11. This definition provides a single-valued estimate of the cumulative ozone depletion for a gas, relative to CFC-11 on an equal mass basis.

One-dimensional and two-dimensional global atmospheric models have determined ODPs for a number of halocarbons, including CFCs, other chlorinated compounds, several potential replacement hydrohalocarbons and several brominated compounds. Table 4.1 gives the range of calculated ODPs from one-dimensional and two-dimensional models for the CFCs, HCFCs, HFCs, plus CCl_4 and CH_3CCl_3. Although 2-D models have generally a sounder physical basis, there are no real differences between the 1-D and 2-D results. In general, the ODPs for fully halogenated compounds, such as the CFCs, are much larger than those for the hydrogenated halocarbons, which include the potential replacement compounds considered.

Table 4.2 gives the ODPs determined for several brominated halocarbons from calculations by two models. These compounds should be compared to each other, because of the strong dependence of bromine effects on ozone to background chlorine levels. Bromine Ozone Depletion Potential (BODPs) are used for relative comparisons with Halon-1301, which has the longest lifetime and largest ODP, as the reference.

Although the calculated ODPs agree reasonably well among models, many uncertainties still exist. None of the models used for calculating ODPs include the chemical and dynamical processes causing the seasonal ozone losses over Antarctica. Another uncertainty lies in the model-calculated OH, which is a major source of uncertainty for both lifetimes and ODPs of the HCFCs.

Because of the apparent special chlorine processing and dynamics within the polar winter vortex, local Antarctic ODPs are expected to be larger than those shown in Table 4.1. Insofar as the observed long-lived tracer distributions, such as CFC-11 in the polar vortex, suggest that much of the total chlorine may be available there, then an upper limit on Antarctic ODPs can be determined by calculating the relative amounts of chlorine transported through the tropopause by the different gases. These chlorine loading potentials (CLPs) determined using assumed reference lifetimes (which generally agree with those in the models used here) can be as large as a factor of two to three times the derived ODP values (c.f., Tables 4.1 and 4.3). The ramifications of polar ozone depletion for global ozone depletion potentials (ODPs) are not currently clear.

The time-dependent relative ozone depletion values differ from the steady-state ODP values. The time-dependent values depend on the atmospheric lifetime and the transport time to the region of destruction of the gas. The shorter the stratospheric lifetime, the sooner the gas will impact stratospheric ozone and hence the higher the transient relative ozone depletion. An example of this behavior is shown by the HCFC-123 curve in Figure 4.1. It has a shorter lifetime than CFC-11; its relative ozone depletion is largest soon after emission. Other gases in this category include HCFC-141b and CH_3CCl_3. Species such as HCFC-22, HCFC-124, and HCFC-142b have somewhat longer time constants in the stratosphere. Their relative ozone depletions build slowly to values (based on their time constants) as large as 0.2 and then decay slowly with time to the derived ODP value. Relative ozone depletion values for HCFCs are greater than ODP values even after 30 to 50 years. Time-dependent relative ozone depletions for CFCs with lifetimes longer than CFC-11 show a monotonic increase to the ODP value. As shown for a pulse injection in Figure 4.2, the ratio of the cumulative calculated depletion of HCFC-22 or HCFC-123 to the cumulative depletion of CFC-11 is equal to the ODP for these species. Therefore, the ODP is the cumulative response; as discussed above, the transient response of relative ozone depletion may be larger that the ODP value at early times after emission.

Several of the halocarbons indicate a strong latitude dependence in their ODP values and a generally weaker seasonal variation. In particular, ODPs for species such as CFC-12, HCFC-22, HCFC-124, and HCFC-142b, which have greatly different stratospheric loss patterns than CFC-11, produce strong latitudinal gradients in ODPs, with the largest ODPs near summer poles and smallest values in the tropics. The effects of heterogeneous chemistry and polar dynamical effects could modify these findings.

Table 4.1. Range of Ozone Depletion Potentials (ODP) determined by one-dimensional and two-dimensional models, assuming scaling for HCFC ODPs by CH_3CCl_3 observed lifetime (6.3 years).

Species	1-D Models*	2-D Models**
CFC-11	1.0	1.0
CFC-12	0.9 - 1.0	0.9
CFC-113	0.8 - 0.9	0.8 - 0.9
CFC-114	0.6 - 0.8	0.6 - 0.8
CFC-115	0.4 - 0.5	0.3 - 0.4
HCFC-22	0.04 - 0.05	0.04 - 0.06
HCFC-123	0.013 - 0.016	0.013 - 0.022
HCFC-124	0.016 - 0.018	0.018 - 0.024
HFC-125	0	0
HFC-134a	0	0
HCFC-141b	0.07 - 0.08	0.09 - 0.11
HCFC-142b	0.05 - 0.06	0.05 - 0.06
HFC-134a	0	0
HFC-152a	0	0
CCl_4	1.0 - 1.2	1.0 - 1.2
CH_3CCl_3	0.10 - 0.12	0.13 - 0.16

* 1-D models from AER, LLNL, DuPont, and IAS

** 2-D models from AER, LLNL, University of Oslo, and DuPont

Table 4.2. Ozone Depletion Potentials for brominated compounds as calculated in the LLNL one-dimensional model and University of Oslo two-dimensional model.

	ODP*		BODP**	
Species	LLNL	Oslo	LLNL	Oslo
Halon-1301	13.2	7.8	1.0	1.0
Halon-1211	2.2	3.0	0.17	0.38
Halon-1202	0.3		0.02	
Halon-2402	6.2	5.0	0.5	0.64

* Relative to CFC-11, shown for historical purposes. Values will be underestimates if account is taken of polar effects. Assumed upper stratospheric Cl_x mixing ratio is 3 ppbv in the LLNL model and 4.5 ppbv in the Oslo model.

** Bromine Ozone Depletion Potentials (BODPs) defined relative to Halon-1301, the longest lived brominated gas.

Table 4.3. Maximum relative Chlorine Loading Potential (CLP) for examined CFCs, HCFCs, HFCs, and other chlorinated halocarbons based on reference species lifetimes chosen to be compatible with available atmospheric measurements and modeling studies.

Species	Reference * Lifetime (yrs)	Chlorine Loading Potentials**
CFC-11	60.0	1.0
CFC-12	120.0	1.5
CFC-113	90.0	1.11
CFC-114	200.0	1.8
CFC-115	400.0	2.0
HCFC-22	15.3	0.14
HCFC-123	1.6	0.016
HCFC-124	6.6	0.04
HFC-125	28.1	0
HFC-134a	15.5	0
HCFC-141b	7.8	0.10
HCFC-142b	19.1	0.14
HFC-143a	41.0	0
HFC-152a	1.7	0
CCl_4	50.0	1.0
CH_3CCl_3	6.3	0.11

* Lifetimes (e-folding time) are based on estimates used in scenario development in Section 3.3.1 for the CFCs and from the analysis in Section 4.2 for the HCFCs and HFCs.

** Chlorine Loading Potential is defined as the maximum chlorine transported across the tropopause per mass emitted relative to the same for CFC-11. It is proportional to lifetime and the number of chlorine atoms per molecule. It is inversely proportional to molecular weight.

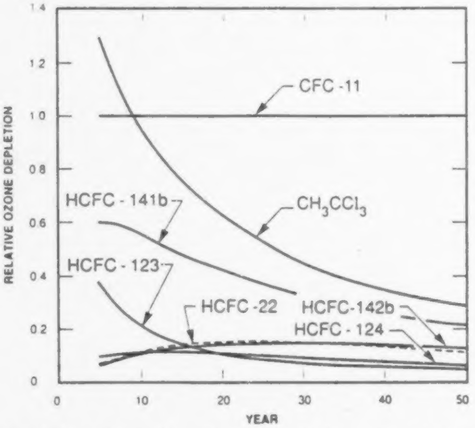
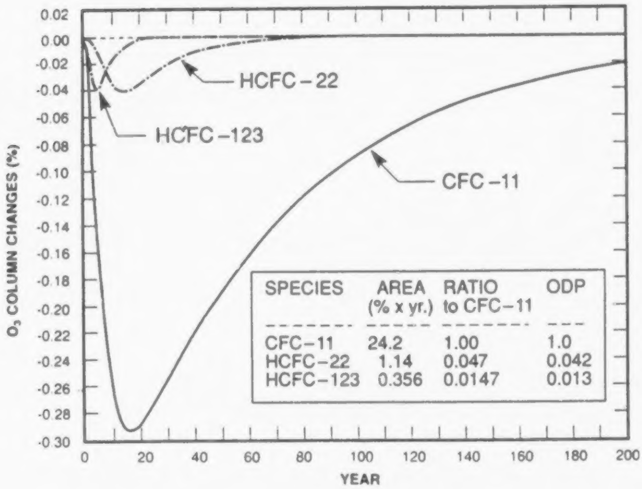


Figure 4.1. Calculated time-dependent change in relative ozone column depletion following a step change in emission of halocarbons (LLNL 1-D model).



SPECIES	AREA (% x yr.)	RATIO to CFC-11	ODP
CFC-11	24.2	1.00	1.0
HCFC-22	1.14	0.047	0.042
HCFC-123	0.356	0.0147	0.013

Figure 4.2. Calculated column ozone change following a pulsed input of 5 x 10^9 kg (for one year) of specified gas (DuPont 1-D model).

Sensitivity analyses indicate that ODPs are affected to only a minor degree (≤ 20%) by assumed variations in background levels of N_2O, CH_4, CO_2, CO, total stratospheric chlorine, and total stratospheric bromine.

4.3 Halocarbon Global Warming Potentials

Halocarbon Global Warming Potential is defined as the ratio of the calculated steady-state net infrared flux change forcing at the tropopause for any halocarbon for each unit mass emitted relative to the same for CFC-11. This definition quantifies the relative cumulative greenhouse warming per unit mass emitted.

Changes in the infrared fluxes in the surface troposphere system have been calculated for a number of halocarbons of these gases using a line-by-line radiative transfer model (GFDL). In addition, radiative forcing and surface temperature changes for these gases have been calculated using two one-dimensional radiative-convective models (AER and DuPont).

Halocarbon Global Warming Potentials (halocarbon GWPs) have been calculated from these results and scaled to a reference set of lifetimes (see Table 4.4). Agreement of ratio values is good, although direct radiative forcing values for individual gases differ systematically among models (between line-by-line and band models).

Halocarbon GWPs for fully halogenated compounds are larger than those for the hydrogenated halocarbons. Fully halogenated CFCs have halocarbon GWP values ranging from 1.0 to 7.5, whereas HCFCs and HFCs range from 0.02 to 0.7.

Halocarbon GWP values differ between species because of differences in infrared absorbances and differences in lifetimes. The range on absorbances is approximately a factor of 4, while the lifetimes vary by a factor of 250. Thus, the range of 600 among the halocarbon GWP values is primarily a result of differences in lifetimes.

Halocarbon GWP values are nearly insensitive to changes in background concentrations of CO_2, CH_4 and N_2O. Minor effects ($\leq$ 20%) do result from influences on chemical lifetimes, but these do not affect the relative radiative forcing.

Calculated time-dependent relative global warmings for halocarbons are initially on order unity, but decrease or increase depending on whether their lifetimes are shorter or longer than that of the reference gas. At long lifetimes the relative global warmings asymptotically approach halocarbon GWP values.

Table 4.4. Halocarbon Global Warming Potentials (Halocarbon GWPs) scaled relative to reference set of halocarbon lifetimes.

Species	Reference* Lifetime(Yrs)	AER**	DuPont**	GFDL**
CFC-11	60.0	1.0	1.0	1.0
CFC-12	120.0	3.4	2.8	3.0
CFC-113	90.0	1.4	1.4	1.3
CFC-114	200.0	4.1	3.7	
CFC-115	400.0	7.5	7.6	7.4
HCFC-22	15.3	0.37	0.34	0.32
HCFC-123	1.6	0.020	0.017	0.017
HCFC-124	6.6	0.10	0.092	
HFC-125	28.1	0.65	0.51	
HFC-134a	15.5	0.29	0.25	0.24
HCFC-141b	7.8	0.097	0.087	0.084
HCFC-142b	19.1	0.39	0.34	0.35
HFC-143a	41.0	0.76	0.72	
HFC-152a	1.7	0.033	0.026	0.028
CCl_4	50.0	0.34	0.35	
CH_3CCl_3	6.3	0.022	0.026	

* Lifetimes are based on estimates used in scenarios development (Section 3.3.1) for CFCs and from the analysis in Section 4.2 for HCFCs and HFCs.

** AER and DuPont results are based on surface temperatures perturbations calculated using radiative-convective models. The GFDL results are based on line-by-line determined radiative forcing.

Volume II

THE AFEAS REPORT

I. SUMMARY

The AFEAS report is the outcome of the Alternative Fluorocarbon Environmental Acceptability Study (AFEAS). AFEAS was organized to evaluate the potential effects on the environment of alternative compounds targeted to replace fuliy halogenated chlorofluorocarbons (CFCs). The objective was to:

Evaluate all relevant current scientific information to determine the environmental acceptability of the alternative fluorocarbons with special emphasis on:

- The potential of the compounds to affect stratospheric ozone,
- Their potential to affect tropospheric ozone,
- Their potential to contribute to model calculated global warming,
- the atmospheric degradation mechanisms of the compounds, in order to identify their products and hence,
- The potential environmental effects of the decomposition products.

The alternative compounds to be studied were hydrofluorocarborns (HFCs) with one or two carbon atoms and one or more each of fluorine and hydrogen and hydrochlorofluorocarbons (HCFCs) with one or two carbon atoms and one or more each of fluorine, chlorine and hydrogen. Because they contain hydrogen atoms, HFCs, and HCFCs are less stable in the atmosphere than CFCs and thus have greatly reduced ozone depletion potentials. Additionally, HFCs do not contain chlorine atoms which are the key factor in ozone depletion. All compounds meeting the above criteria were evaluated where data exists but emphasis was placed on evaluating the following.

HCFC 123	$CC1_2HCF_3$
HCFC 141b	$CC1_2FCH_3$
HCFC 142b	$CC1F_2CH_3$
HCFC 22	$CC1F_2H$
HCFC 124	$CC1FHCF_3$
HFC 134a	CF_3CFH_2
HFC 152a	CF_2HCH_3
HFC 125	CF_3CF_2H

There were 52 scientists worldwide involved in AFEAS. Experts prepared review papers on all aspects of the topic and each paper was reviewed by one or more scientists. In addition, model calculations were carried out on ozone depletion and halocarbon global warming potentials. A meeting was held in Boulder, Colorado in May 1989 under the chairmanship of Dr. R. T. Watson of the National Aeronautics and Space Administration (NASA) for experts and reviewers to discuss and reach a consensus. The papers in this report are the outcome of that meeting. Summaries of these papers formed part of the 1989 UNEP Science Assessment.

AFEAS was conducted by independent scientists but was organized and sponsored by fifteen CFC producers from around the world as part of cooperative industry efforts to study the safety and environmental acceptability of CFC alternatives.

This report consists of the individual papers prepared for the Boulder meeting, revised to take account of reviewers' opinions and discussion. They are arranged in sections according to subject matter. Where there is more than one paper on a topic, a combined summary and conclusions was prepared to introduce the papers in that section.

II. PHYSICAL PROPERTIES

Physical Properties of Alternatives to the Fully Halogenated Chlorofluorocarbons

by M. O. McLinden

This section is concerned with physical properties of possible alternatives to the fully halogenated Chlorofluorocarbons (CFCs) used as refrigerants, solvents, and foam blowing agents. Specifically considered are the fixed points of the fluids (triple point and boiling point temperatures, and critical temperature, pressure, and density), vapor pressure, saturated liquid density, solubility in water, and hydrolysis rates. These properties directly or indirectly influence the fate of a chemical in the environment and also include the key thermophysical data necessary to estimate other properties. The fluids considered are hydrogen-containing halogenated methanes and ethanes. Included are R125, R22, R134a, R152a, R124, R142b, R123, R141b, and methyl chloroform.

A wide variety of data sources have been considered including published data, surveys and compilations of properties, and unpublished data provided by several of the companies which are members of the Alternative Fluorocarbon Environmental Acceptability Study (AFEAS) consortium. These data have been compiled and evaluated. Recommended values are tabulated for the fluid fixed points. The temperature dependencies of vapor pressure, saturated liquid density and solubility in pure water are presented in terms of correlations and as a tabulation of values calculated from these correlations.

The data vary greatly in quality and reliability, and are sometimes conflicting. At least limited data were available for the fixed points, vapor pressure and liquid density of all of the compounds. The values presented here are felt to be reasonable, although the lack of documentation in many cases makes an objective assessment of accuracy impossible, and revisions will certainly be necessary as additional data become available. Identified as high priority needs are improved vapor pressure data for R124, R142b, and, especially R141b, and improved liquid density data for R142b.

For solubility in water, the data were much more limited. Published, fully documented data were available only for R22. For the other fluids, unpublished data provided by the chemical manufacturers were used; again, while these data may be reliable, an assessment of their accuracy was not possible. The solubility information was correlated in terms of the Henry's law constant. The use of Henry's law in extrapolating from the saturation vapor pressure condition's employed in most of the measurements to the extremely low partial pressures that can be expected in the atmosphere is a source of uncertainty. For solubility in salt water, only data for R22 and methyl chloroform were found; an empirical 'salting parameter' evaluated from data for these two fluids can be applied to the other fluids in the absence of data.

Finally, hydrolysis is considered. Hydrolysis represents one possible mechanism for the environmental decomposition of a compound dissolved in the oceans or in cloud water. The data for hydrolysis rates were quite sparse; except for R22 and methyl chloroform, recommended values could not be developed. In view of the very limited solubilities of these compounds, even the order of magnitude-type information that can be estimated or extrapolated from the available data may be sufficient to determine whether dissolution in water and subsequent hydrolysis is a significant destruction mechanism for these compounds. Thus, complete data on solubility and hydrolysis may be needed only for methyl chloroform. This point is considered in detail in a study by Wine and Chameides presented in Section VII, Liquid Phase Processes.

III. REACTION RATE CONSTANTS

Evaluated Rate Constants for Selected HCFCs and HFCs with OH and O(^{1}D)

by R. F. Hampson, M. J. Kurylo and S. P. Sander

The chemistry of HCFCs and HFCs in the troposphere is controlled by reactions with OH in which a hydrogen atom is abstracted from the halocarbon to form water and an halo-alkyl radical. The halo-alkyl radical subsequently reacts with molecular oxygen to form a peroxy radical. The reactions of HCFCs and HFCs with O(^{1}D) atoms are unimportant in the troposphere but may be important in producing active chlorine or OH in the stratosphere.

In this chapter, the rate constants for the reactions of OH and O(^{1}D) with many HFCs and HCFCs have been evaluated. Recommendations are given for the five HCFCs and three HFCs specified by AFEAS as primary alternatives as well as for all other isomers of C_1 and C_2 HCFCs and HFCs where rate data exist. In addition, recommendations are included for CH_3CCl_3, CH_2Cl_2, and CH_4.

The format used for the presentation of the recommended rate constant data is the same as that used by the NASA Panel for Data Evaluation (see DeMore et al., JPL Publication 87-41, September 15, 1987). The rate constant tabulation is given in Arrhenius form, $k(T) = A \exp(-E/RT)$, and contains the following information:

1. Reaction stoichiometry and products (if known).
2. Arrhenius A factor (in units of cm^3 $molecule^{-1}$ s^{-1}.
3. Temperature dependence ("activation temperature," E/R) and associated uncertainty (Δ E/R).
4. Rate constant at 298 K (in units of cm^3 $molecule^{-1}$ s^{-1}.
5. Uncertainty factor at 298 K.

All of the uncertainties are one standard deviation, 1σ. Hence, 95% confidence limits are given by 2σ. The uncertainty (1σ) at any temperature can be calculated from the expression:

$$f(T) = f(298)\exp\{\Delta E/R(1/T - 1/298)\}$$

For all of the OH reactions, the recommendations were derived from linear least squares Arrhenius fits of the selected data bases for temperatures below 400 K. This temperature restriction was made due to the observed Arrhenius curvature for several of the reactions over more extended temperature ranges. For some reactants, the necessary temperature dependent data do not exist, and the E/R values were estimated by comparison with other similar reactants and the A factor back-calculated using k_{298}. Reasonable values of E/R can be estimated from compounds appearing in a homologous series and by noting that most values of E/R for reactions of OH with halocarbons lie between 1000 and 2000 K. An alternative approach would have involved estimating, or calculating from transition state theory, the A factor and using k_{298} to obtain E/R. These two approaches yield similar results if the data are not extrapolated very far from room temperature and, thus, are nearly equivalent for the calculation of ozone depletion or greenhouse warming potentials. These two estimation procedures can result in significant differences when used for extrapolations over a wide temperature range. In addition, they can yield disparate predictions when there are no direct kinetic data for either the species of interest or for one of similar structure.

Recommended rate constants and uncertainties for reactions of OH with selected HFCs and HCFCs.

Reaction	Fluorocarbon Number	A[1]	E/R ± ΔE/R[2]	k_{298}[1]	f(298)
OH + $CHFCl_2$	HCFC-21	1.2(-12)	1100 ± 150	3.0(-14)	1.1
OH + CHF_2Cl	HCFC-22	1.2(-12)	1650 ± 150	4.7(-15)	1.1
OH + CHF_3	HFC-23	1.5(-12)	2650 ± 500	2.1(-16)	1.5
OH + CH_2Cl_2	30	5.8(-12)	1100 ± 250	1.4(-13)	1.2
OH + CH_2FCl	HCFC-31	3.0(-12)	1250 ± 200	4.5(-14)	1.15
OH + CH_2F_2	HFC-32	2.5(-12)	1650 ± 200	1.0(-14)	1.2
OH + CH_3F	HFC-41	5.4(-12)	1700 ± 300	1.8(-14)	1.2
OH + CH_4	50	2.3(-12)	1700 ± 200	7.7(-15)	1.2
OH + $CHCl_2CF_3$	HCFC-123	6.4(-13)	850 ± 250	3.7(-14)	1.2
OH + $CHFClCF_3$	HCFC-124	6.6(-13)	1250 ± 300	1.0(-14)	1.2
OH + CHF_2CF_3	HFC-125	8.9(-13)	1750 ± 500	2.5(-15)	2.0
OH + CH_2ClCF_2Cl	HCFC-132b	3.6(-12)	1600 ± 400	1.7(-14)	2.0
OH + CH_2ClCF_3	HCFC-133a	5.2(-13)	1100 ± 300	1.3(-14)	1.3
OH + CHF_2CHF_2	HFC-134	8.7(-13)	1500 ± 500	5.7(-15)	2.0
OH + CH_2FCF_3	HFC-134a	1.7(-12)	1750 ± 300	4.8(-15)	1.2
OH + CH_3CCl_3	140	5.0(-12)	1800 ± 300	1.2(-14)	1.3
OH + CH_3CFCl_2	HCFC-141b	4.2(-13)	1200 ± 300	7.5(-15)	1.3
OH + CH_3CF_2Cl	HCFC-142b	9.6(-13)	1650 ± 250	3.8(-15)	1.2
OH + CH_2FCHF_2	HFC-143	2.8(-12)	1500 ± 500	1.8(-14)	2.0
OH + CH_3CF_3	HFC-143a	6.0(-13)	1750 ± 500	1.7(-15)	2.0
OH + CH_2FCH_2F	HFC-152	1.7(-11)	1500 ± 500	1.1(-13)	2.0
OH + CH_3CHF_2	HFC-152a	1.5(-12)	1100 ± 200	3.7(-14)	1.1
OH + CH_3CH_2F	HFC-161	1.3(-11)	1200 ± 300	2.3(-13)	2.0

1 units are cm^3 $molecule^{-1}$ s^{-1}

2 units are K

Rate constants for the $O(^1D)$ reactions are associated with actual chemical reaction (leading to chemical breakdown of the HCFC or HFC) and do not include contributions due to simple physical deactivation (quenching) of the excited oxygen atom. Temperature data do not exist for most of the $O(^1D)$ reactions and the estimated temperature independencies are taken from comparisons with the few HCFCs and CFCs for which such data do exist. The following two tables summarize the results of this evaluation.

Recommended rate constants and uncertainties for reactions of $O(^1D)$ with selected HFCs and HCFCs.

Reaction	Fluorocarbon Number	A^1	$E/R \pm \Delta E/R^2$	k_{298}^1	f(298)
$O(^1D) + CHFCl_2$	HCFC-21	1.9(-10)	0 ± 100	1.9(-10)	1.3
$O(^1D) + CHF_2Cl$	HCFC-22	1.0(-10)	0 ± 100	1.0(-10)	1.3
$O(^1D) + CHF_3$	HFC-23	1.9(-12)	0 ± 500	1.9(-12)	3.0
$O(^1D) + CH_2F_2$	HFC-32	5.0(-11)	0 ± 100	5.0(-11)	2.0
$O(^1D) + CH_3F$	HFC-41	1.0(-10)	0 ± 100	1.0(-10)	2.0
$O(^1D) + CHCl_2CF_3$	HCFC-123	2.3(-10)	0 ± 100	2.3(-10)	2.0
$O(^1D) + CHFClCF_3$	HCFC-124	1.0(-10)	0 ± 100	1.0(-10)	3.0
$O(^1D) + CHF_2CF_3$	HFC-125	5.0(-11)	0 ± 100	5.0(-11)	2.0
$O(^1D) + CH_2ClCF_2Cl$	HCFC-132b	1.7(-10)	0 ± 100	1.7(-10)	2.0
$O(^1D) + CH_2ClCF_3$	HCFC-133a	1.6(-10)	0 ± 100	1.6(-10)	2.0
$O(^1D) + CH_2FCF_3$	HFC-134a	5.0(-11)	0 ± 100	5.0(-11)	3.0
$O(^1D) + CH_3CFCl_2$	HCFC-141b	1.5(-10)	0 ± 100	1.5(-10)	3.0
$O(^1D) + CH_3CF_2Cl$	HCFC-142b	1.4(-10)	0 ± 100	1.4(-10)	2.0
$O(^1D) + CH_3CF_3$	HFC-143a	6.0(-11)	0 ± 100	6.0(-11)	2.0
$O(^1D) + CH_3CHF_2$	HFC-152a	1.0(-10)	0 ± 100	1.0(-10)	3.0

1 units are cm^3 $molecule^{-1}$ s^{-1}

2 units are K

IV. ABSORPTION CROSS SECTIONS

Review of Ultraviolet Absorption Cross Sections of a Series of Alternative Fluorocarbons
by M. J. Molina

Solar photolysis is likely to contribute significantly to the stratospheric destruction of those alternative fluorocarbons (HFCs) which have two or more chlorine atoms bonded to the same carbon atom. Two of the eight HFCs considered in this review fall into this category, namely HFC-123 and HFC-141b. For these two species there is good agreement among the various measurements of the ultraviolet cross sections in the wavelength region which is important for atmospheric photodissociation, that is, around 200 nm. There is also good agreement for HFC-124, HFC-22 and HFC 142b; these are the three species which contain one chlorine atom per molecule. The agreement in the measurements is poor for the other species, i.e. those that do not contain chlorine, except in so far as to corroborate that solar photolysis should be negligible relative to destruction by hydroxyl radicals.

V. TROPOSPHERIC OH AND HCFC/HFC LIFETIMES

The Tropospheric Lifetimes of Halocarbons and their Reactions with OH Radicals: An Assessment Based on the Concentration of ^{14}CO
by R.G. Derwent and A. Volz-Thomas

Tropospheric Hydroxyl Concentrations and the Lifetimes of Hydrochlorofluorocarbons (HCFCs)
by M.J. Prather

The atmospheric lifetime of HCFCs is determined predominantly by reaction with tropospheric OH. Stratospheric loss is secondary and may contribute at most 10% of the total budget.

The lifetimes of HCFCs are determined here by three separate approaches:

(1) 2-D chemical transport model with semi-empirical fit to ^{14}CO;
(2) photochemical calculation of 3-D OH fields and integrated loss;
(3) scaling of the inferred $CH_3\,CCl_3$ lifetime by rate coefficients.

Resulting lifetimes from all three independent approaches generally agree within 15%, as shown in the table below. The integrated losses calculated from the global OH fields in the models (1 & 2) are constrained by modelling of the observations and budgets for ^{14}CO and CH_3CCl_3 (respectively). Method (3) may be expressed simply as

$$\text{lifetime (HCFC)} = 6.3 \text{ yr} \times k(CH_3\,CCl_3 \text{ at } 277\text{ K}) / k(\text{HCFC at } 277\text{ K}),$$

where the current estimate of the lifetime for methyl chloroform (6.3 yr) is based on the ALE/GAGE analysis (Prinn et al., 1987). Some of the errors associated with this scaling have been tested with the 3-D OH fields from method (2); method (3) should be reliable for calculating HCFC lifetimes in the range 1 to 30 years.

The calculated local concentrations of OH in these models (1 & 2) are not well tested since there are few observations of OH with which to compare. Based on method (2), the middle tropical troposphere (2-6 km) dominates the atmospheric loss and would be an important region in which to make observations of OH.

Estimated uncertainties in the HCFC lifetimes between 1 and 30 years are ± 50% for (1) and ± 40% for (2) & (3). Global OH values that give lifetimes outside of these ranges of uncertainty are inconsistent with detailed analyses of the observed distributions for ^{14}CO and CH_3CCl_3. The expected spatial and seasonal variations in the global distribution of HCFCs with lifetimes of 1 to 30 yr have been examined with methods (1) & (2) and found to have insignificant effect on the calculated lifetimes. Larger uncertainties apply to gases with lifetimes shorter than one year; however, for these species our concern is for destruction on a regional scale rather than global accumulation.

Future changes in the oxidative capacity of the troposphere, due to changing atmospheric composition, will affect HCFC lifetimes and introduce additional uncertainties of order ± 20%.

Atmospheric Lifetimes for HCFCs

	k (cm^3 molec^{-1} s^{-1})		**lifetime (yr) for method***		
HCFC			**(1)**	**(2)**	**(3)**
CH_3CCl_3	5.0×10^{-13}	exp(-1800/T)	5	5.4	6.3
(range)			(3-7)	(4-7)	(5.4-7.5)
CH_3F	5.4×10^{-12}	exp(-1700/T)	3.3	3.8	4.1
CH_2F_2	2.5×10^{-12}	exp(-1650/T)	6.0	6.8	7.3
CHF_3	7.4×10^{-13}	exp(-2350/T)	635.	289.	310.
CH_2FCl	3.0×10^{-12}	exp(-1250/T)	1.26	1.33	1.44
$CHFCl_2$	1.2×10^{-12}	exp(-1100/T)	1.80	1.89	2.10
CHF_2Cl (22)	1.2×10^{-12}	exp(-1650/T)	13.0	14.2	15.3
CH_3CH_2F	1.3×10^{-11}	exp(-1200/T)	0.31	0.25	0.28
CH_2FCH_2F (152a)	1.7×10^{-11}	exp(-1500/T)	0.60	0.58	0.63
CH_3CHF_2	1.5×10^{-12}	exp(-1100/T)	1.46	1.53	1.68
CH_2FCHF_2	2.8×10^{-12}	exp(-1500/T)	3.2	3.5	3.8
CH_3CF_3	2.6×10^{-13}	exp(-1500/T)	40.	38.	41.
CHF_2CHF_2	8.7×10^{-13}	exp(-1500/T)	10.4	11.4	12.3
CH_2FCF_3 (134a)	1.7×10^{-12}	exp(-1750/T)	13.1	14.4	15.5
CHF_2CF_3 (125)	3.8×10^{-13}	exp(-1500/T)	24.9	26.1	28.1
CH_3CFCl_2 (141b)	2.7×10^{-13}	exp(-1050/T)	6.7	6.7	7.8
CH_3CF_2Cl (142b)	9.6×10^{-13}	exp(-1650/T)	16.6	17.8	19.1
CH_2ClCF_2Cl	3.6×10^{-12}	exp(-1600/T)	3.5	4.0	4.2
CH_2ClCF_3	5.2×10^{-13}	exp(-1100/T)	4.1	4.4	4.8
$CHCl_2CF_3$ (123)	6.4×10^{-13}	exp(-850/T)	1.40	1.42	1.59
$CHFClCF_3$ (124)	6.6×10^{-13}	exp(-1250/T)	5.5	6.0	6.6

*Lifetimes from method (1) do not include stratospheric loss; those from method (2) include small additional stratospheric loss. Method (3) is based on scaling the methylchloroform lifetime of 6.3 yrs from Prinn et al. (Science, 238, 945-950, 1988) by the ratio of the rate coefficients at 277 K.

VI. DEGRADATION MECHANISMS

Tropospheric Reactions of the Haloalkyl Radicals Formed from Hydroxyl Radical Reaction with a Series of Alternative Fluorocarbons
by R. Atkinson

Degradation Mechanisms of Selected Hydrochlorofluorocarbons in the Atmosphere: An Assessment of Current Knowledge
by R. A.Cox and R. Lesclaux

An Assessment of Potential Degradation Products in the Gas-Phase Reactions of Alternative Fluorocarbons in the Troposphere
by H. Niki

Atmospheric Degradation Mechanisms of Hydrogen Containing Chlorofluorocarbons (HCFCs) and Fluorocarbons (HFCs)
by R. Zellner

Tropospheric reaction with the OH radical is the major and rate determining loss process for the HFCs and HCFCs in the atmosphere.

There are virtually no experimental data available concerning the subsequent reactions occurring in the atmospheric degradation of these molecules. By consideration of data for degradation of alkanes and chloroalkanes it is possible to postulate the reaction mechanisms and products formed in the troposphere from HCFCs and HFCs. However, the results are subject to large qualitative and quantitative uncertainty, and may even be incorrect.

The current level of support for laboratory work is inadequate to enable significant improvement in the state of knowledge in this area in the near future.

Using the above mentioned analysis, a large variety of chlorine and fluorine containing intermediate products such as hydroperoxides, peroxynitrates, carbonyl halides, aldehydes and acids can be expected from the degradation of the 8 proposed CFC substitutes. These are listed in the accompanying table.

Based on the available knowledge of gas phase chemistry only four of these products appear to be potentially significant carriers of chlorine to the stratosphere. These are $CClFO$, CF_3CClO, $CClF_2CO_3NO_2$ and $CCl_2FCO_3NO_2$. However physical renewal processes may reduce this potential. In addition, the possibility of pathways and products not predicted by the arguments-by-analogy are a cause for concern.

A large part of the uncertainty of the mechanistic details of the HCFC oxidation arises from all insufficient knowledge of the thermal stability and reactivity of halogenated alkoxyradicals. In particular, the mechanism of oxidation of the CF_3O radical, which is assumed to produce CF_2O, is not known for atmospheric conditions and needs further study.

Particular attention should be paid to obtaining data on the photochemistry, gas phase reactivity and solubility of the carbonyl, acetyl and formyl halides, in order to assess their removal rates and mechanisms.

Based on current knowledge, the products identified are unlikely to cause significant changes to the effective greenhouse warming potential of the 8 proposed CFC substitutes. This conclusion would be modified if long-lived products such as CF_3H were formed by unidentified pathways.

Laboratory tests and atmospheric measurements are urgently needed to test the validity of the proposed degradation mechanisms for HCFCs and HCFs.

Fluorine-containing products in the atmospheric degradation of selected fluorocarbons.

Compound	Formula	Atom & Radical	Carbonyl	Acid	Hydroxide	Nitrate
HCFC 123	$HCCl_2CF_3$	CF_3CCl_2OO			CF_3CCl_2OOH	$CF_3CCl_2OONO_2$
		CF_3CCl_2O	CF_3CClO			
		CF_3OO			CF_3OOH	CF_3OONO_2
		CF_3O			CF_3OH	CF_3ONO_2
HCFC 141B	CCl_2FCH_3	CCl_2FCH_2OO			CCl_2FCH_2OOH	$CCl_2FCH_2OONO_2$
		CCl_2FCH_2O	CCl_2FCHO			
		CCl_2FOO			CCl_2FOOH	CCl_2FOONO_2
		CCl_2FO	$CClFO$			
		$CCl_2FC(O)OO$		$CCl_2FC(O)OOH$		$CCl_2FC(O)OONO_2$
				$CCl_2FC(O)OH$		
HCFC 142b	$CClF_2CH_3$	$CClF_2CH_2OO$			$CClF_2CH_2OOH$	$CClF_2CH_2OONO_2$
		$CClF_2CH_2O$	$CClF_2CHO$			
		$CClF_2OO$			$CClF_2OOH$	$CClF_2OONO_2$
		$CClF_2O$	CF_2O			
		$CClF_2C(O)OO$		$CClF_2(O)OOH$		$CClF_2C(O)OONO_2$
				$CClF_2C(O)OH$		
HCFC 22	$CHClF_2$	$CClF_2OO$			$CClF_2OOH$	$CClF_2OONO_2$
		$CClF_2O$	CF_2O			
HCFC 124	$CHClFCF_3$	$CF_3CClFOO$			$CF_3CClFOOH$	$CF_3CClFOONO_2$
		CF_3CClFO	CF_3CFO			
		CF_3OO			CF_3OOH	CF_3OONO_2
		CF_3O			CF_3OH	CF_3ONO_2
HCF 134a	CH_2FCF_3	CF_3CHFOO			$CF_3CHFOOH$	$CF_3CHFOONO_2$
		CF_3CHFO	$CHFO$			
			CF_3CHFO			
		CF_3OO			CF_3OOH	CF_3OONO_2
		CF_3O			CF_3OH	CF_3ONO_2
		CFO			$CF(O)OOH$	$CF(O)OONO_2$
HFC 52a	CHF_2CH_3	CH_3CF_2Oo			CH_3CF_2OOH	$CH_3CF_2OONO_2$
		CH_3CF_2O	CF_2O			
		CHF_2CH_2OO			CHF_2CH_2OOH	$CHF_2CH_2OONO_2$
		CHF_2CH_2O	CHF_2CHO			
		CHF_2OO			CHF_2OOH	CHF_2OONO_2
		CHF_2O	$CHFO$			
		$CHF_2C(O)OO$		$CHF_2C(O)OOH$		$CHF_2C(O)OONO_2$
				$CHF_2C(O)OH$		
		CFO		$CF(O)OOH$		$CF(O)OONO_2$
HCF 125	CHF_2CF_3	CF_3CF_2OO			CF_3CF_2OOH	$CF_3CF_2OONO_2$
		CF_3CF_2O	CF_2O			
			CF_3CFO			
		CF_3OO			CF_3OOH	CF_3OONO_2
		CF_3O			CF_3OH	CF_3ONO_2

VII. LIQUID PHASE PROCESSES

Possible Atmospheric Lifetimes and Chemical Reaction Mechanisms for Selected HCFCs, HFCs, CH_3CCl_3, and their Degradation Products Against Dissolution and/or Degradation in Seawater and Cloudwater

by P.H. Wine and W.L. Chameides

The rates at which eight potential alternative HCFCs and HFCs and methyl chloroform (CH_3CCl_3) can be removed from the atmosphere by dissolution and reaction in the oceans and in cloudwater have been estimated from the species' thermodynamic and chemical properties using simple mathematical formulations to simulate the transfer of gases from the atmosphere to the aqueous phase. The HCFCs and HFCs considered are $CHCl_2CF_3$ (HCFC-123), $CFCl_2CH_3$, (HCFC-141b), CF_2ClCH3 (HCFC-142b), CHF_2Cl (HCFC-22), $CHFClCF_3$, (HCFC-124), CH_2FCF_3 (HFC-134a), CHF_2CH_3 (HFC-152a), and CHF_2CF_3 (HFC-125).

Cloudwater is found to be of no importance as an atmospheric sink for any of the above compounds. Best-estimate lifetimes for all eight HCFCs and HFCs toward removal in the oceans are greater than 77 years, with only HCFC-22, HCFC-123, and HCFC-141b having lifetimes shorter than 200 years. The most reactive of the nine species considered toward removal in the oceans is methyl chloroform with a best-estimated lifetime of 42 years and a minimum reasonable lifetime of 22 years. Important removal mechanisms for methyl chloroform, HCFC-22, HCFC-123, and HCFC-141b in seawater are hydrolysis and reaction with hydrated electrons. Improved hydrolysis kinetics data and Henry's law solubility data for methyl chloroform HCFC-22, HCFC-123, and HCFC-141b in seawater are hydrolysis and reaction with hydrated electrons. Improved hydrolysis kinetics data and Henry's law solubility data for methyl chloroform, HCFC-22, HCFC-123, and HCFC-141b would help to reduce the uncertainties in the aqueous phase removal rates of these species, as would improved estimates of the hydrated electron concentration in water.

Gas phase degradation products of the eight HCFCs and HFCs include a large variety of halo-substituted carbonyls, acids, peroxyacids, hydroperoxides, alcohols, nitrates, peroxynitrates, and peroxyacetylnitrates. Although handicapped by the total absence of Henry's law solubility data for any of the compounds of interest and the limited availability of relevant kinetic data, an assessment of the rates and mechanisms of aqueous phase removal of the gas phase degradation products has been carried out.

The species X_2CO, $HXCO$, CH_3CXO, CF_3OH, CX_3OONO_2 and ROOH ($X = F$ or Cl, R = halosubstituted methyl or acetyl) are all expected to be removed from the atmosphere on time scales limited by transport to cloudy regions or the marine boundary layer (i.e. about 1 month); aqueous phase reactions of these species result in the formation of chloride, fluoride, and carbon dioxide, as well as formic, acetic, and oxalic acids. The species CX_3CXO, CX_3CX_2OOH, $CX_3CX_2OONO_2$, $CX_3C(O)OONO_2$, and $CX_3C(O)OOH$ are also expected to be removed from the atmosphere rapidly, and their aqueous phase reactions result in the formation of halo-substituted acetates, $CX_3C(O)O^-$.

The species $CX3C(O)OH$ are very acidic and, as a result, are highly soluble in cloudwater. These acids are expected to be rapidly removed from the atmosphere by rainout. However, the aqueous phase species $CX_3C(O)O^-$ are expected to be resistant to chemical degradation. Trichloroacetate can thermally decompose on a time scale of 2-10 years to yield carbon dioxide and chloroform. In fresh water, the reaction of $CCl_3C(O)O^-$, with the hydrated electron is also expected to occur on a time scale of a few years. The species $CFCl_2C(O)O^-$, $CF_2ClC(O)O^-$ and

$CF_3C(O)O^-$ may have very long aqueous phase lifetimes. The longest lived species, $CF_3C(O)O^-$, could have a lifetime in natural waters as long as several hundred years. Processes which could possibly degrade $CF_nCl_{3-n}C(O)O^-$ on shorter times scales than suggested above, but whose rates cannot be estimated with any degree of confidence at this time, include oxidation by photochemically generated valence band holes in semiconductor particles and hydrolysis catalyzed by enzymes in microorganisms and plants; further research aimed at characterizing these processes is needed.

One possible gas phase degradation product about very little is known is CF_3ONO_2. This compound has never been observed, and may be thermally unstable. If CF_3ONO_2 is thermally stable, then it may have a long lifetime toward aqueous phase removal. Henry's law solubility data and hydrolysis kinetics data for CF_3ONO_2 are needed before its aqueous phase removal rate can be assessed with any degree of confidence

VIII. OZONE DEPLETION POTENTIALS

Relative Effects on Stratospheric Ozone of Halogenated Methanes and Ethanes of Social and Industrial Interest

by D.A. Fisher, C.H.Hales, D.L. Filkin, M.K.W. Ko, N.D. Sze, P.S. Connell,
D.J. Wuebbles, I. S. A. Isaksen, and F. Stordal

Ozone Depletion Potentials (ODPs) have been defined and calculated in order to allow estimates of the relative effects of halocarbons on stratospheric ozone. Models using representations of homogeneous atmospheric chemical processes have estimated relative effects on global ozone. These estimates indicate that the ODPs of the hydrohalocarbons are generally one-tenth or less those of the CFC-11 and -12. The reduction in ODP that might be expected due to replacement of uses of a CFC by a hydrohalocarbon can be estimated by taking the ratio of the ODP of the hydrohalocarbon to the ODP of the CFC it might replace. For example, the reduction in ODP in replacing uses of CFC-12 by HCFC-22 is $(0.049 \pm .015)/(.93) = .053 \pm .015$. Of course, the relative quantities of the compound required in the use application must also be taken into account.

Although the values of ODPs reported here agree reasonably well among models, uncertainties in the values still exist due to the uncertainties in modeled chemistry and dynamics. Since reaction with OH dominates the chemistry of the HCFCs, uncertainties in the model calculated OH values remain a major source of uncertainty for both lifetimes and ODPs of these compounds. Uncertainties for some compounds may be reduced with new laboratory data on the ultraviolet absorption properties and the rate constants with hydroxyl for the HCFCs and HFCs.

Sensitivity analyses reveal that the global ODP values are affected to only a minor degree by the levels of N_2O, CH_4, CO_2, CO, and Brx used in model calculations. Latitudinal relative effects on ozone depletion depend on the species — species with high altitude sinks show more latitudinal dependency than CFC-11. Those species destroyed in the lower stratosphere have latitudinal effects equivalent to CFC-11. Seasonal variation of relative ozone depletions are second order.

Another major uncertainty centers on the potential effects of heterogeneous chemistry in the lower stratosphere, particularly near the poles in winter-time. While these effects are believed to cause the Antarctic springtime ozone decreases, they are not included in any of the model calculations of ODPs. Due to the cold stratospheric temperatures, polar stratospheric clouds become activation sites for chlorine compounds (by-products from the decomposition of the chlorocarbons) resulting in increased chlorine catalytic loss for ozone. Since ODP is defined relative to CFC-11, the effect of including heterogeneous chemistry will have little effect on the local ODP value compared to values determined assuming only homogeneous chemistry. However, polar contribution to global ozone loss would be greater such that global ODP values would be more heavily weighted by the polar values. Thus, species with large, positive latitudinal gradients in ODP would have global ODPs that are fractionally increased. On the other hand, inclusion of stronger polar dynamics would affect both the transport and the distribution of chlorine species and would directly impact both the local and global ODP values.

Upper bounds are placed on the local effects by a chlorine loading potential, i.e., the relative amount of chlorine added to the stratosphere by a given gas. A less conservative estimate derived from the relative values of Cly in the lower polar stratosphere in spring indicates that the potential effect can be substantially less than the Chlorine Loading Potential but would be above the homogeneous chemistry ODP value. The geographic extent of the heterogeneous effect on global ODP outside of the polar vortex is impossible to estimate at the present time.

Time-dependent Relative Ozone Depletions and Relative Chlorine Loading for HCFCs have values above the ODP and CLP values derived from steady-state calculations. For longer lived CFCs, the time-dependent values are always less than the ODP and CLP values.

Range of Ozone Depletion Potentials (ODP) determined by 1-D and 2-D models, assuming scaling for HCFC ODPs by CH_3CCl3 observed lifetime (6.3 years).

Species	1-D Models*	2-D Models**
CFC-11	1.0	1.0
CFC-12	0.9-1.0	0.9
CFC-113	0.8-0.9	0.8-0.9
CFC-114	0.6-0.8	0.6-0.8
CFC-115	0.4-0.5	0.3-0.4
HCFC-22	0.4-0.05	0.04-0.06
HCFC-123	0.013-0.016	0.013-0.022
HCFC-124	0.016-0.018	0.017-0.024
HFC-125	0	0
HFC-134a	0	0
HCFC-141b	0.07-0.08	0.09-0.11
HCFC-142b	0.05-0.06	0.05-0.06
HFC-134a	0	0
HFC-152a	0	0
CCl_4	1.0-1.2	1.0-1.2
CH_3CCl_3	0.10-0.12	0.13-0.16

* 1-D models from AER, LLNL and DuPont.

** 2-D models from AER, LLNL, University of Oslo, and DuPont.

IX. HALOCARBON GLOBAL WARMING POTENTIALS

Relative Effects on Global Warming of Halogenated Methanes and Ethanes of Social and Industrial Interest
by D.A. Fisher, C. H. Hales,
Wei-Chyung Wang, M.K.W. Ko and N.D. Sze

Halocarbon Global Warming Potentials have been defined and calculated in order to allow estimates of the relative environmental effects of halocarbons to be made. The results presented here indicate that the HGWPs of the hydrohalocarbons depend primarily on the atmospheric lifetime of the compounds and to a lesser degree on the molecular IR absorption characteristics.

The reduction in HGWP that might be expected due to use replacement of a CFC by a hydrohalocarbon can be estimated by taking the ratio of the HGWP of the hydrohalocarbon to the HGWP of the CFC it would replace. For example, the reduction in HGWP in replacing uses of CFC-12 by HCFC-134a is $(0.26 \pm .010)/(3.05) = 0.085 \pm 0.003$. Of course, the relative quantities of the compound required in the use application must also be taken into account.

Although the HGWP values reported here agree between models reasonably well once accounting is made for the differences in lifetimes, uncertainties in the values still exist due to the uncertainties in modeled chemistry and dynamics and their direct effect on the chemical lifetimes of these compounds. We expect that these values will be updated once better data is available for the ultraviolet reactions and the hydroxyl radical reactions with the respective compounds.

The HGWP values appear to be reasonably robust parameters since their calculated values are nearly insensitive to assumed values of other radiative gases. The minor shifting of the HGWP values in primarily influenced by the changes in calculated lifetimes and therefore the abundance in the atmosphere.

Calculated time-dependent relative global warmings for halocarbons are initially on order unity but decrease or increase depending on whether their lifetimes are shorter than that of the reference gas. At longer times, the Relative Global Warmings asymptotically approach the HGWP values.

X. IMPACT ON PHOTOCHEMICAL OXIDANTS INCLUDING TROPOSPHERIC OZONE

An Assessment of Potential Impact of Alternative Fluorocarbons on Tropospheric Ozone
by H. Niki

One type of tropospheric impact of the alternative halocarbons may arise from their possible contribution as precursors to the formation of O_3 and other oxidants on urban and global scales. In the present assessment the following specific issues related to tropospheric oxidants are addressed:

1. Is it likely that the HFCs and HCFCs would contribute to production of photochemical oxidants in the vicinity of release?

2. On a global basis, how would emissions of HCFCs and HCFs compare to natural sources of O_3 precursors?

Since almost all CFCs are emitted in urban environments, the first question deals primarily with urban "smog" formation. Salient features of chemical relationships between oxidants and their precursors as well as the relevant terminologies are described briefly in order to provide a framework for the discussion of these two issues.

Based on an analysis of the atmospheric concentrations of various O_3 precursors, and their atmospheric reactivity and O_3 forming potential, the maximum projected contributions of the alternative fluorocarbons to O_3 production in both urban and global atmospheres have been derived as follows:

1: Urban Atmosphere (values in parenthesis in units of 10^{-3}% of the total contribution of all O_3 precursors):

HFCs: CH_3CHF_2-152a (59), CH_2FCF_3-134a (8), CHF_2CF_3-125 (4)

HCFCs: $CHC1F_2$-22 (8), CH_3CC1F_2-142b (6), CH_3CHC1F-124 (16),

CH_3CC1_2F-141b (13), $CHC1CF_3$-123 (59)

2: Global Atmosphere (values in parenthesis in units of 10^{-3}% of the total contribution of all O_3 precursors):

HFCs: CH_3CHF_2-152a (92), CH_2FCF_3-134a (11), CHF_2CF_3-125 (7)

HCFCs: $CHC1F_2$-22 (11), CH_3CC1F_2-142b (10), CH_3CHC1F-124 (25),

CH_3CC1_2F-141b (20), $CHC1CF_3$-123 (92)

XI. NATURAL SOURCES

Natural Chlorine and Fluorine in the Atmosphere, Water and Precipitation

by J.P. Friend

The geochemical cycles of chlorine and fluorine are surveyed and summarized as framework for the understanding of the global natural abundances of these species in the atmosphere, water and precipitation. In the cycles the fluxes into and out of the atmosphere can be balanced within the limits of our knowledge of the natural sources and sinks. Sea salt from the ocean surfaces represent the predominant portion of the source of chlorine. It is also an important source of atmospheric fluorine, but volcanos are likely to be more important fluorine sources. Dry deposition or sea salt returns about 85% of the salt released there. Precipitation removes the remainder. Most of the sea salt material is considered to be cyclic, moving through sea spray over the oceans and either directly back to the oceans (about 90%) or deposited dry and in precipitation on land (about 10%), whence it runs off into rivers and streams and returns to the oceans. Most of the natural chlorine in the atmosphere is in the form of particulate chloride ion with lesser amounts as gaseous inorganic chloride (most likely HIC) and methyl chloride vapor. Fluorine is emitted from volcanos primarily as HF. It is possible that HF may be released directly from the ocean surface but this has not been confirmed by observation. HCl and most likely HF gases are released into the atmosphere by sea salt aerosols. The mechanism for the release is likely to be the provision of protons from the so-called excess sulfate (that which results from the oxidation of SO_2) and HNO_3. Sea salt aerosol contains fluorine as F^-, MgF^+ and CaF^+ and NaF. The concentrations of the various species of chlorine and fluorine that characterize primarily natural, unpolluted atmospheres are summarized in tables and are discussed in relation to their fluxes through the geochemical cycle.

XII. BIOLOGICAL AND HEALTH EFFECTS

Toxicology of Atmosphere of Atmospheric Degradation Products of Selected Hydrochlorofluorocarbons
by L.S. Kaminsky

Assessment of Effects on Vegetation of Degradation Products from Alternative Fluorocarbons
by D.C. McCune and L.H. Weinstein

There is a need for more information on exposure, especially to organic breakdown products. This should include estimates of ground level concentrations, modes of deposition (wet and dry) and should extend to identification of half-lives in soil and water, and the products of microbial transformation.

Nothing is known of the toxicology to humans, animals or plants of any of the organic breakdown products other than trifluoroacetic acid. It was considered dubious to extrapolate from analogous compounds (e.g. trichloroacetic acid). The limited work on toxicology of TFA was with very high concentrations compared with those potentially arising from HCFCs and CFCs. Studies should aim to determine the long-term threshold level for toxicological effects.

One of the major uncertainties is the fate of $-CF_3$ as there is conflict of opinion about the stability of the C-F bond. The biological evidence (from toxicology and pesticide biochemistry) indicates that $-CF_3$, is recalcitrant and may persist in the environment but an opinion was expressed that there may be significant chemical defluorination at room temperature. Because of the mammalian toxicity of monofluoracetate, the possibility of defluorination of trifluoro- to monofluoro- needs to be firmly clarified.

In contrast with position regards organic products, and notwithstanding uncertainties about rates of deposition, it can be stated with a high degree of confidence that inorganic fluoride (HF) does not present a significant risk to human, animals, plants, or soil.

Likewise HCl is of no direct risk to humans, animals or plants. Acidity from inorganic acids or as a result of mineralization of organic products does not add any significant burden to the environment in the form of acid deposition.

SECTION C

Transient Scenarios for Atmospheric Chlorine and Bromine

Michael J. Prather and Robert T. Watson
NASA Headquarters, Code SEU, Washington, DC 20546

1.0 INTRODUCTION

The rise in atmospheric chlorine levels due to the industrial production and emission of chlorofluorocarbons (CFCs) and other halocarbons is now believed to be the cause of the dramatic appearance of the Antarctic ozone hole in the late 1970s. Further increases in the chlorine and bromine content of the stratosphere are inevitable over the next decade, and the consequences for ozone abundances over the Antarctic, Arctic and the globe are uncertain. Only stringent controls over the production of chlorine-containing hydrocarbons will enable our atmosphere to return to chlorine abundances prevalent prior to the occurrence of the ozone hole, about 2 ppb (parts per billion = molecules per 10^9 molecules of air).

Bromine in the stratosphere, present at concentrations of about 0.02 ppb, also contributes globally to ozone loss. The role of bromine, as BrO, in formation of the Antarctic ozone hole has been demonstrated but not yet been fully quantified. Catalytic cycles involving BrO and ClO are greatly enhanced in the Antarctic ozone hole relative to the rest of the stratosphere. During the austral spring of 1987, bromine is estimated to be responsible for 10 to 30% of the ozone depletion with chlorine alone responsible for the majority.

A sensitivity study of chlorine-loading scenarios is presented for a range of global emissions for compounds currently regulated under the Montreal Protocol (CFC-11 = $CFCl_3$, CFC-12 = CF_2Cl_2, CFC-113 = $CF_2ClCFCl_2$, CFC-114 = CF_2ClCF_2Cl, CFC-115 = CF_3CF_2Cl), for other gases not specified in the Montreal Protocol (carbon tetrachloride = CCl_4, methyl chloroform = CH_3CCl_3, HCFC-22 = CHF_2Cl), and for possible new hydro-halocarbon substitutes (HCFCs). A subset of these scenarios is also shown for atmospheric bromine loading, being driven by the increases in the halons listed under the Montreal Protocol (CF_3Br, CF_2ClBr, $C_2F_4Br_2$) with fixed levels of CH_3Br.

After complete cessation of all halocarbon emissions, the decline in atmospheric chlorine levels below 2 ppb is determined by the decay of the long-lived CFCs produced prior to the phaseout and would not occur until the latter half of the 21st century. We show here that the use of short-lived HCFC substitutes would not significantly affect this time scale if the substitutes were eliminated sometime between 2030 and 2050, depending on the lifetime of the substitute. The elimination of the Antarctic ozone hole sometime in the future relies predominantly on reducing chlorine levels to 2 ppb or less, but will also depend in part on the local meteorology and changes in other trace gases such as methane.

The maximum concentration of atmospheric chlorine that will be reached in the next several decades is controlled by the amount of chlorine-containing halocarbons (CFCs, CCl_4, CH_3CCl_3, and HCFC-22) added to the atmosphere thus far, and by the amount that will be produced and eventually released to the atmosphere prior to a complete phaseout. The scenarios shown here demonstrate the obvious result that the key factor in reducing the peak chlorine loading is the rapid cutback in CFC emissions. They also show the less evident result that substitution of modest amounts of short-lived HCFCs for the CFCs will not increase the maximum chlorine levels.

Scenarios for Cl and Br

Largest ozone depletions in the future are expected to coincide with the peak chlorine loading of the atmosphere. Global-scale losses, largest in the upper stratosphere, are predicted from the gas-phase chemical reactions of chlorine monoxide with atomic oxygen. Ozone depletion throughout the stratosphere in the southern mid-latitudes may become more extensive if the Antarctic ozone hole enlarges. Over Antarctica, and possibly in the Arctic, losses are driven by chlorine-catalyzed destruction of ozone following heterogeneous reactions on polar stratospheric clouds in winter. The rapid appearance of the ozone hole over the last decade demonstrates the extremely non-linear response of polar ozone to increasing chlorine levels. We must be prepared for new thresholds of accelerated ozone loss in the Arctic as chlorine concentrations continue to rise above the current (record) levels of about 3 ppb.

2.0 CHLORINE LOADING AND ODPs

The atmospheric chlorine loading is calculated here as the instantaneous, bulk tropospheric mixing ratio (ppb) of chlorine atoms in the form of all the halocarbons noted above, plus the natural source CH_3Cl (0.6 ppb). This definition of chlorine loading of the atmosphere is a conservative (maximum) measure of the amount of stratospheric chlorine that may be active in catalytic ozone destruction because not all of the chlorine will be available (i.e., photochemically released from the halocarbon source gas). For the year 1985, the table below gives the relative contribution of the individual gases to the total chlorine loading (3.0 ppb). The projected chlorine loading can be used to demonstrate the contribution of individual halocarbons to overall chlorine levels as a function of time.

Atmospheric Chlorine Loading in the Year 1985

industrial sources	
CFC-11	22 %
CFC-12	25 %
CFC-113	3 %
CFC-114	<1 %
CFC-115	<1 %
HCFC-22	3 %
carbon tetrachloride	13 %
methyl chloroform	13 %
natural sources	
methyl chloride	20 %

The Ozone Depletion Potential (ODP) of a halocarbon is calculated with a chemical model for stratospheric ozone, assuming that the gas is in steady state between emissions and atmospheric loss. For most CFCs the time to approach within 10% of steady-state conditions is more than a century. The ODP of a halocarbon is defined relative to CFC-11 (dimensionless) rather than in absolute units (e.g., % ozone loss per kg of gas emitted). Greenhouse Warming Potentials (GWP) are calculated similarly with a model for steady-state climate change. ODPs (or GWPs) therefore reflect the relative chronic ozone destruction (or warming potential) of CFCs after nearly constant emissions for a century. Transient ozone depletion potentials have also been used, but they do not clearly reflect the contribution of different halocarbons to the amount of chlorine in the atmosphere over the next century.

Even in the limit of steady state, the relative chlorine loading of a halocarbon can differ from its ODP because the calculation of an ODP includes the effectiveness of the gas in releasing its chlorine within the stratosphere. Most of the chlorine atoms in CFC-11 are released by photolysis in the lower stratosphere and thus are available to participate in the catalytic destruction of ozone at all altitudes in the stratosphere. Other CFCs, such as CFC-12 and HCFC-22, are more slowly photolyzed; in the lower stratosphere much of their chlorine is retained in the halocarbon; and most of their chlorine atoms are available only in the upper stratosphere or in the winter polar stratosphere. (Air in the winter polar stratosphere appears to be photochemically aged, having descended from the upper stratosphere.) For such compounds, the model derived ODPs (relative to CFC-11) will be less than the relative chlorine loading in these scenarios. A warning about the accuracy of ODP calculations must be made: the current assessment models are limited to gas-phase chemistry and predict future ozone depletion predominantly in the middle stratosphere; they do not predict the Antarctic ozone hole or the possibility of similar heterogeneously driven ozone loss in the Arctic lower stratosphere.

The following scenarios were constructed as a sensitivity study to examine several possible approaches to limiting atmospheric chlorine content. The scenarios for the halocarbon source gases are similar, but not identical, to those used to calculate ozone depletion by the UNEP/WMO assessment. Two particular differences are that the lifetime of HCFC-22 is assumed here to be 15 years (rather than 20 years) based on more recent analyses of HCFC lifetimes, and that the assumed CFC cutback in emissions occurs entirely at the end of a given year rather than being phased in over 5 years from 1996 to 2000.

3.0 THE MODEL FOR CHLORINE/BROMINE LOADING

The data for halocarbons used in the model for chlorine and bromine loading are based on compilations from the recent ozone assessment (UNEP/WMO, 1990) and the workshop on alternative fluorocarbons (AFEAS, 1990). The data and method of calculating the mean abundance of the halocarbons are given in Table 1. The atmospheric lifetimes in Table 1 are taken from these recent reports and have an estimated uncertainty of 25 %. Lifetimes for those species destroyed predominantly in the troposphere (CH_3CCl_3 and HCFC-22) are based on the AFEAS review. The fluxes in Table 1 (1 kt/yr = 1,000 metric tons per yr) are based on estimates of production in the year 1985 and total 1,000,000 metric tons for CFCs alone. Growth in production from 1985 through 1990 (kt/yr per yr) is assumed to be 4 %/yr for all industrial halocarbons; such increases are consistent with growth in the production of CFC-11 and CFC-12, compounds for which we have reliable estimates. The initial concentrations in 1985 (parts per trillion $=1/10^{12}$) represent a tropospheric average based on available observations (IOTP, 1990). The factor (kt/ppt) used to convert mixing ratio (ppt) to total abundance (kt) assumes the compound is well mixed throughout 95 % of the atmosphere.

A simple numerical model is used: for example, the concentration in 1986 is calculated by reducing the 1985 value by a factor equal to exp[-1/lifetime(yr)] and then by adding the total emissions in 1986 which have also been reduced by a factor depending on the lifetime (see notes in Table 1). Thus, concentrations refer to the end of the specified year. Fluxes of CFCs and all other chlorine- and bromine-containing species, except CH_3Cl and CH_3Br, are defined according to the scenario, and cuts are assumed to take place instantly at the end of the specified year. More accurate numerical models for the calculation of halocarbon concentrations are available. For example, such models might include the effects of the delay between production and emission of CFCs according to use, of shifts in atmospheric circulation due to climate change, or of changes in tropospheric chemistry (e.g., HCFC and CH_3CCl_3 losses) due to increasing concentrations of other gases such as methane. However, increasing the complexity of the model is not justified for this work because uncertainties (e.g., lifetimes, see Objective 7; release of chlorine in the stratosphere, see ODP discussion) overwhelm the differences between such models.

The reference scenario assumes control over atmospheric emissions of all industrial halocarbons as a group (CFCs, CCl_4, HCFC-22, CH_3CCl_3 and the halons). It begins in 1985,

Table 1. Halocarbon Data for Model

Halocarbon		Lifetime (yr)	Flux (kt yr^{-1})	Growth (kt $yr^{-1}yr^{-1}$)	Concen-tration (ppt)	Factor (kt ppt^{-1})
CFC-11	$CFCl_3$	60	360	14.4	220	23.2
CFC-12	CF_2Cl_2	120	450	18.0	375	20.4
CFC-113	$C_2F_3Cl_3$	90	165	6.6	30	31.6
CFC-114	$C_2F_4Cl_2$	200	15	0.6	5	28.9
CFC-115	C_2F_5Cl	400	10	0.4	4	26.1
Carbon tetrachloride	CCl_4	50	80	3.2	100	25.9
HCFC-22	CHF_2Cl	15	140	5.6	80	14.6
methylchloroform	CH_3CCl_3	6	600	24.0	130	22.4
methylchloride	CH_3Cl	1.5			600	
(sub. X)	C_xCl	15			0	19.3
(sub. Y)	C_xCl	6			0	19.3
halon-1211	CF_2BrCl	15	10	0.40	1.5	27.9
halon-1301	CF_3Br	110	9	0.36	1.7	25.1
methylbromide	CH_3Br	1.5			15	

Lifetime (yr) is the global abundance divided by the annual average loss rate.
Flux (kt/yr = 1,000 tons per year) equals the atmospheric emissions during 1985.
Growth (kt/yr/yr) equals the increment to the flux each year from 1986 through 1990.
Concentration (ppt = parts per trillion = $1/10^{12}$) is the average (well mixed) tropospheric abundance in 1985.
Factor (kt/ppt) relates concentration (ppt) to global content (kt).
Methyl chloride and methyl bromide concentrations are fixed.
The concentration (conc) in year+1 is calculated from the equation:

conc[year+1] = conc[year] x decay + flux[year+1] x (1-decay) x lifetime / factor
where decay = exp(-1 / lifetime).

assumes growth for the years 1986 through 1990, freezes emissions into the atmosphere at the 1990-rate, and cuts all emissions to zero at the end of the year 2000. From then on the atmospheric abundance of chlorine or bromine is determined solely by the slow decay of gases already in the atmosphere in this reference scenario. Under the current Montreal Protocol the cutback to 50% of CFC emissions refers to 1986 production levels. Also, the earlier implementation of these reductions may result in smaller emissions during the period 1990-2000 than in this scenario.

4.0 TIME DELAYS AND BANKING OF CFCs

The absolute timing of the atmospheric response in these calculations may be imprecise not only due to the basic uncertainties in modeling atmospheric composition, but also because certain simplifying assumptions have been made. For example, stratospheric destruction of halocarbons (predominant loss for the long-lived CFCs) will lag emissions by about 2 years, the time it takes for air to travel from the upper troposphere to the middle stratosphere. This effect will be important only when tropospheric concentrations are changing rapidly and is not included here. Furthermore, the ozone depletion in response to halocarbons will also be delayed by the time for tropospheric air to circulate through the stratosphere. Air over the winter pole may represent a mix of tropospheric halocarbons from as long ago as 5 years previous.

A more important and obviously systematic omission in these calculations is the failure to simulate the delay between halocarbon production and emissions (see CMA, 1988). Depending on use, the halocarbons produced in a given year may not be emitted into the atmosphere until several years later. For examples, CFC-11 used in blowing closed-cell insulating foams may take more than 10 years to escape into the atmosphere, and CFC-12 used in hermetically sealed refrigeration systems will not be released until the refrigerant coils break, on average 20 years later. The accumulation, or banking, of the CFCs makes it difficult to stop emissions (as in the reference scenario) immediately upon cessation of production. On the other hand, CFC-113 and CH_3CCl_3 are used primarily as cleaning agents, and their production reflects the amount lost during the cleaning process, presumably to the atmosphere. Most of the CFCs are used in products that release the gases to the atmosphere within 3 years of production. The total bank of CFCs as of 1987 in products with average retention times greater than 2 years is estimated to be less than 2 years of the annual production of all CFCs (CMA, 1988). The net effect of CFC banking may look similar to the scenario in which there is a 15-year delay in compliance with CFC cuts (Objective 4 below); however, the banking may be offset by partial cuts in CFCs before the year 2000 as already agreed upon in the current Montreal Protocol.

In spite of these uncertainties in the timing of atmospheric effects, we expect that the comparison between scenarios, such as the difference in peak chlorine loading or the variance in times to reach 2 ppb chlorine, will be accurate. These scenarios describe controls over emissions rather than production and, with this caveat, the calculations provide a useful relative measure of the potential damage to stratospheric ozone associated with each option.

5.0 SUBSTITUTION

Substitution for the phased-out halocarbons is considered in many scenarios. In such cases we assume a kg-per-kg replacement (in %) of the sum of halocarbon cuts referenced to their 1985 emission levels (1,000 kt/yr of CFCs, 80 kt/yr of CCl_4, 140 kt/yr of HCFC-22, 600 kt/yr of CH_3CCl_3). We are interested here only in substitutes containing chlorine or bromine. The chemical industry has estimated that replacement with chlorinated compounds would capture about 30% of the CFC market (350 kt/yr in 1985). Substitution for CCl_4, HCFC-22 and CH_3CCl_3--if these compounds were phased out--are likely not to involve chlorinated replacements. Hence, in the reference scenario with a complete cut in all halocarbons (1,820 kt/yr in 1985), the industry estimates would correspond to a substitution rate of about 20% in these scenarios. We have not considered the possibility of bromine-containing compounds as substitutes for the halons.

Two substitute chemicals are considered as replacements for the reductions in the industrial halocarbons (CFCs, CCl_4, HCFC-22, and CH_3CCl_3):

- compound X has a 15 year lifetime (like HCFC-22) with a single chlorine atom and a mean molecular weight of 115, corresponding to a steady-state chlorine loading factor of 0.10 relative to CFC-11;
- compound Y has a 6 year lifetime (like CH_3CCl_3) with a single chlorine atom and a mean molecular weight of 115, corresponding to a steady-state chlorine loading factor of 0.04 relative to CFC-11.

These substitutes are examples of the types of alternative halocarbons included by AFEAS (1990) in its review of alternative fluorocarbons, but do not correspond to any specific compound. Choosing substitute X to replace some of the cutbacks in CFCs, CCl_4, CH_3CCl_3, and HCFC-22, is almost equivalent to continuing, and possibly expanding, the use of HCFC-22. The chlorine loading of HCFC-22 is slightly larger, 0.13, but its ODP is currently modelled to be smaller, 0.05, as discussed above. Thus substitute X would mimic the temporal behavior of HCFC-22 with a slightly different scale factor for its emissions (in kg). Similarly, substitute Y would mimic CH_3CCl_3 but has only one chlorine.

6.0 OBJECTIVES

Possible environmental goals might be based on the levels of atmospheric chlorine in the past. Some key chlorine abundances to remember are: (1) the natural abundance of chlorine is 0.6 ppb; (2) chlorine levels in the Antarctic stratosphere before the ozone hole were 1.5 to 2.0 ppb; and (3) today's abundance of chlorine is about 3.0 ppb.

One could not expect the depletion of Antar~~ctic ozone~~ to cease much before the middle of the next century when atmospheric chlorine concentrations would reach 2 ppb or less under the most stringent controls over halocarbon emissions. In order to return to near pristine conditions below 1 ppb chlorine, however, we must wait for the longest-lived CFCs to be almost completely destroyed in the atmosphere. Even without further emissions, this condition would not be met until well into the 22nd century. Without the ozone hole, the difference between 1 and 2 ppb of chlorine is predicted to lead to small, less than 2%, changes in global column ozone (IOTP, 1990).

A number of scenarios were performed to understand what possible actions control the peak chlorine loading, the rate at which the atmospheric abundance of chlorine decreases, and the date at which the atmospheric abundance of chlorine drops below 2 ppb. Specific objectives involve the testing of the impact of:

1. the timing of a phaseout (100% cut) in CFCs, CCl_4, CH_3CCl_3, and HCFC-22 (complete phaseout without substitution in 1995, 2000 [reference case] and 2005);
2. incomplete phaseout (cut in 2000 to 10%, 20%, 50% of 1985 emissions, or freeze the 1990 emissions);
3. different substitution scenarios for compound X and compound Y (phaseout of all halocarbons in 2000 with varying % substitution of X and Y by weight continued until 2015, 2030, 2045 and even 2100);
4. delayed compliance of phaseout by some countries (cut back to 10% or 20% of 1985 emissions in 2000, complete phaseout in 2015, any substitution is similarly lagged by 15 years);
5. graduated phase-in of halocarbon cuts (cut halocarbon emission to 50% of 1985 emissions in 1995 and completely phaseout in 2000; substitutes have similar 5 yr phase lag);
6. continued use of CH_3CCl_3 (freeze emissions of CH_3CCl_3 at 1990 levels, phaseout in 2030);
7. current uncertainties in the atmospheric lifetimes of halocarbons;
8. halon emissions on bromine loading (cut emissions of CF_3Br and CF_2ClBr in 2000 to 0%, 10%, 20%, 50% of 1985 emissions, or freeze at 1990 levels).

The chlorine loading from these scenarios is summarized in Tables 2a-h and the bromine loading in Table 3. Figures 1-12 display the evolution of chlorine from 1985 to 2100 for a selection of these cases and always compare with the reference calculation (complete phaseout of CFCs, CCl_4, CH_3CCl_3, and HCFC-22 emissions in the year 2000 with no substitutions).

6.1 OBJECTIVE 1. Test the impact of the timing of a phaseout (100% cut) in CFCs, CCl_4, CH_3CCl_3, and HCFC-22

This objective was examined by eliminating the emissions of all halocarbons as a group (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) at the end of years 1995, 2000 (reference case), and 2005, all without substitution of any new chlorine containing compound.

Table 2a and Figure 1 show the results of these scenarios. (Tables 2a-2-h and Table 3 follow at the end in order to provide easy reference.) It is evident that each 5 year delay in the total phaseout of these chemicals results in the peak chlorine loading increasing by about 0.5 ppb (87% of it due to the CFCs) and in the date taken for the atmospheric abundance of chlorine to drop below 2 ppb increasing by about 18 years. The delay in reaching an atmospheric loading of 2 ppb is due to the timing of the phaseout of the long-lived halocarbons (CFCs and CCl_4) and is not influenced by the timing of the phaseout of short-lived halocarbons (CH_3CCl_3 and HCFC-22). Banking of these gases, especially the long-lived CFCs, and possible non-compliance (see Objectives 2 and 4), make the effective dates for cessation of CFC emissions slip further into the future.

The key information from these scenarios is that an early phaseout of these substances results in a lower peak chlorine loading (0.1 ppb per year earlier phaseout) and in an earlier date for the atmospheric chlorine loading to drop below 2 ppb (3.6 years per year earlier phaseout), corresponding to the most optimistic time for elimination of the Antarctic ozone hole. The table below summarizes the peak chlorine loading and the date of 2 ppb chlorine for these scenarios.

Peak Chlorine Loading and Time to Reach 2 ppb

scenario (phaseout=100% cut)	peak chlorine (ppb)	year when chlorine falls below 2 ppb
1995 phaseout	4.24	2055
2000 phaseout (ref#)	4.78	2073
2005 phaseout	5.28	2091

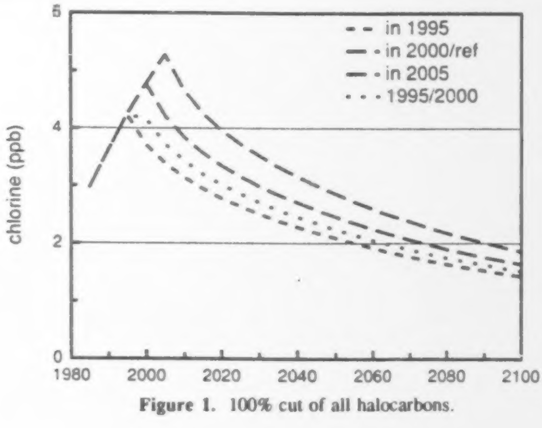


Figure 1. 100% cut of all halocarbons.

6.2 OBJECTIVE 2. Test the impact of incomplete phaseout.

This objective examined the impact of a partial phaseout (90%, 80%, 50%, 0%) in the emissions of all halocarbons as a group (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) without substitution of any new chlorine containing compound. All reductions (90%, 80% and 50%) were made to reach a fraction of the year 1985 emissions (10%, 20% and 50% respectively), and all occurred at the end of year 2000. The calculation with no reductions continued the year 1990 emission levels of all halocarbons until the year 2100.

Table 2a and Figure 2 show the results of these scenarios. For partial phaseouts of 90% and 80% the peak chlorine loading is not affected, but the rate of decrease in the atmospheric chlorine and its long-term steady state value are significantly impacted. In the reference case (100% reduction) the atmospheric abundance of chlorine has decreased to 2 ppb by the year 2073. With a 90% reduction the chlorine abundance reaches 2.4 ppb in the year 2100 and is not expected to decrease to 2 ppb until after the year 2175. With an 80% reduction the chlorine abundance is 3.1 ppb in the year 2100 and will eventually approach its steady-state limit of about 2.8 ppb. With 50% reductions the peak chlorine loading drops briefly after the year 2000 and then continues to rise above 5.3 ppb by the year 2100. Without a cutback in the 1990 emissions the chlorine abundance in the atmosphere is expected to rise rapidly, exceeding 8.5 ppb by the year 2050 and 10.5 ppb by the end of the 21st century.

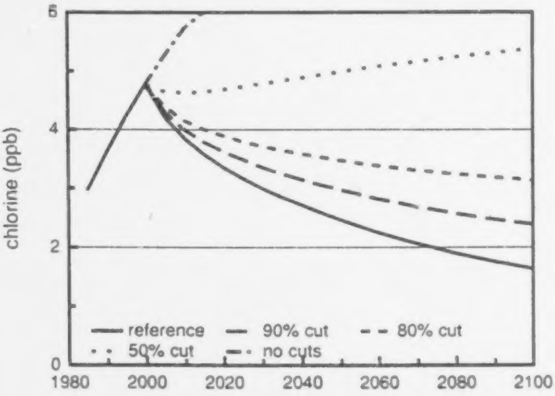


Figure 2. Cut all halocarbons in 2000.

The key conclusion to be drawn from these scenarios is that a complete phaseout of almost all emission of halocarbons (CFCs, CCl_4, CH_3CCl_3, and HCFC-22) as a group is needed in order to decrease the atmospheric abundance of chlorine below 2 ppb before the year 2100. The required timing of these phaseouts will depend on the lifetime of the specific halocarbon. The long-term decline in chlorine abundances is controlled by the long-lived CFCs and CCl_4. Therefore, a long-term non-compliance with the 100% reduction, by even as little as 5 to 10%, limits our chance of eliminating the Antarctic ozone hole before the year 2100. The table below summarizes the peak chlorine loading and the date of 2 ppb chlorine for these scenarios.

Peak Chlorine Loading and Time to Reach 2 ppb

scenario (phaseout=100% cut)	peak chlorine (ppb)	year when chlorine falls below 2 ppb
2000 phaseout (ref#)	4.78	2073
2000 (90% cut)	4.78	2175
2000 (80% cut)	4.78	never

6.3 OBJECTIVE 3. Test the impact of different substitution scenarios for compound X and compound Y

This objective was examined by eliminating the emissions of the halocarbons (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) as a group in the year 2000 (reference case) and then by substituting for a fraction of these emissions (1,820 kt/yr) with either compound X (15 year lifetime, ODP = 0.1) or compound Y (6 year lifetime, ODP = 0.04). Substitution of either X or Y begins in the year 2001 at a level of 25%, 50% or 100%, corresponding to annual fluxes of 455, 910 and 1,820 kt, respectively. In addition, a scenario with 50% substitution is considered in which use of the substitute (X or Y) is allowed to grow annually at a compounded rate of 3 %/yr (denoted by *50%). In general, the time period of substitution is assumed to be 30 years, from year 2001 through year 2030. In some cases the period of substitution is shortened to 15 years or extended to 45 or even 100 years.

Tables 2b-d and Figures 3-6 show the results of these many scenarios. We discuss only a few of them below.

For the levels of substitution and the limits on their growth considered in these scenarios, the peak chlorine loading occurs at the phaseout of CFCs and is not affected by the substitution. In the case of 100% substitution of compound X, however, the chlorine loading remains high, above 4 ppb, out to the year 2032 (Figure 3). Equivalent substitution of compound Y has a much smaller impact on atmospheric chlorine because of the shorter lifetime (Figure 4). Substitution by either compound X or Y at 50% of the halocarbon emissions followed by 3 %/yr compounded growth becomes equivalent to 100% substitution by the year 2030 and would greatly exceed that level if continued for another 15 years (Figures 3 and 4).

Substitution between the years 2000 and 2030 with compound X at less than 25%, or compound Y at less than 50% of all halocarbon emissions, results in a rapid decrease in peak chlorine loading. The increase in atmospheric chlorine abundance above the base case (no substitution) is

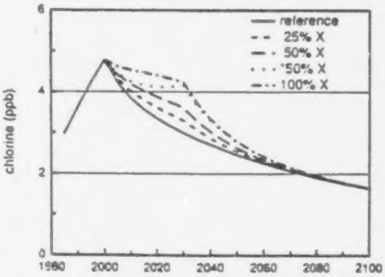


Figure 3. Substitution for 30 yrs (*=growth).

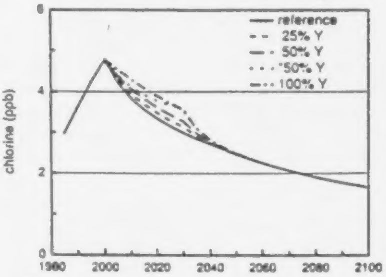


Figure 4. Substitution for 30 yrs (*=growth)..

greatest in the year 2030 and never exceeds 0.3 ppb under these conditions. The assessment of the International Technical Panel (part of the UNEP assessment) is that about 30% of the current CFC market will be replaced by short-lived substitutes containing chlorine, and that this market will grow at 3 %/yr until terminated. Such a scenario is about equivalent to following the 25% substitution-curve in the early years (2000-2010) and increasing to chlorine levels slightly above the 50% substitution-curve by the year 2030.

When compound X is phased out before the year 2030 or compound Y before the year 2045, the earliest date when the atmospheric abundance of chlorine falls to 2 ppb is delayed by at most 4 years relative to the reference case with no substitutions (Figure 5). With indefinite substitution of compound X or Y, even at 50% of the halocarbon emissions, it is difficult or impossible to achieve chlorine concentrations below 2 ppb by the end of the 21st century (Figure 6).

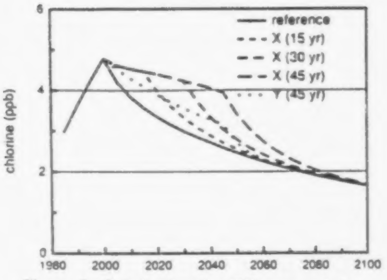


Figure 5. Substitution for different periods.

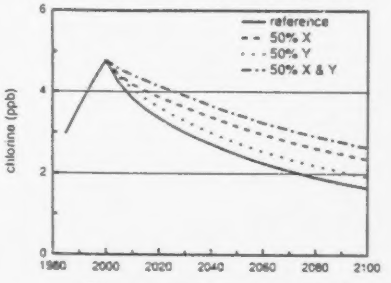


Figure 6. Substitution until 2100.

The key conclusions to be drawn from these scenarios are that substitution of all halocarbons (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) as a group, between the years 2000 and 2030 by compound X, and between the years 2000 and 2045 by compound Y, would have little influence on the date when the atmospheric abundance of chlorine can be expected to fall below 2 ppb, approximately the year 2073. With a limited period of substitution of the short-lived substitutes, the chlorine loading of the atmosphere beyond the year 2075 is governed by the CFCs and CCl_4 emitted prior to their phaseout. Furthermore, such substitutions can still result in a rapid decrease in the peak chlorine abundance if substitution rates close to 25% for X or 50% for Y are used. Substitution by compound Y is preferable to substitution by compound X because of its shorter lifetime: compound Y makes a smaller contribution to the chlorine loading and in addition allows for more rapid recovery of atmospheric chlorine following cessation of emissions.

6.4 OBJECTIVE 4. Test the impact of delayed compliance of phaseout by some countries.

This objective was examined by reducing emissions of all halocarbons (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) to a fraction (10% or 20%) of their 1985 levels in the year 2000 and allowing this fraction of emissions to continue for 15 years until the end of year 2015. Substitution of compounds X and Y was also considered as above for a 30-year time period. The final phaseout of CFCs in the year 2015 was followed by a similar period of fractional substitution until the year 2045. This form of delayed compliance would allow a fraction of the world community further time to implement a complete halocarbon phaseout.

Table 2e and Figures 7-8 show the results of these scenarios. There is no additional penalty in the peak chlorine loading for a 15-year lag in the final 10% or 20% of the halocarbon cuts. However, the 15-year lag in 10% of the phaseout results in a 6-year delay in the time to reach 2 ppb chlorine, and the lag in 20% adds 11 years to this time. The effects of substitution of

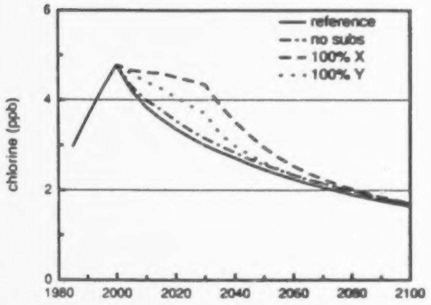


Figure 7. 10% of CFC cuts/subs lag 15 yr.

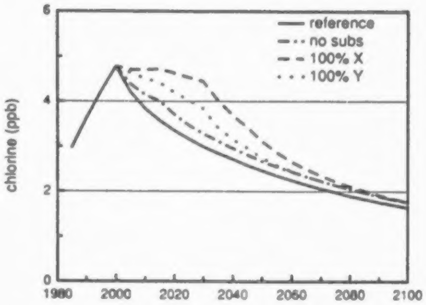


Figure 8. 20% of CFC cuts/subs lag 15 yr.

compounds X or Y are similar to the reference case (complete phaseout) except that the baseline of total chlorine is higher during the substitution period, by a maximum in the year 2015 of about 0.2 ppb (10%) and 0.4 ppb (20%). The 15-year delay in the phaseout does extend the duration of higher chlorine levels. In the case where only 80% of the CFCs are cut and replaced 100% by compound X, the peak chlorine loading in the year 2000 (4.78 ppb) is maintained out to the year 2015 (4.72 ppb).

The key point here is that a 15-year lag in compliance of the phaseout of CFCs by a *small fraction*, 10-20%, of the community should have no effect on peak chlorine levels and have only a small delay in the time to reach 2 ppb total chlorine. The average chlorine levels in the first half of the next century would be higher in this scenario, but may be compensated for by reducing use of the longer-lived of the two substitutes, compounds X. The table below summarizes the peak chlorine loading and the date of 2 ppb chlorine for these scenarios.

Peak Chlorine Loading and Time to Reach 2 ppb

scenario (phaseout=100% cut)	peak chlorine (ppb)	year when chlorine falls below 2 ppb
2000 phaseout (ref#)	4.78	2073
2000/2015 (90/10%)	4.78	2079
2000/2015 (80/20%)	4.78	2084

6.5 OBJECTIVE 5. Test the impact of a graduated phase-in of halocarbon cuts.

This objective was examined by reducing the emissions of all halocarbons (CFCs, CCl_4, CH_3CCl_3 and HCFC-22) to 50% of their 1985 levels at the end of year 1995 and completely to zero at the end of year 2000. Substitution of compound X or Y for a period of 30 years (staggered 5 years as for halocarbon cuts) at 50% of the 1985 halocarbon emissions is also considered. This complex scenario for phaseout of CFCs may be a more realistic approach to elimination of halocarbon emissions, recognizing the ability of some parts of the CFC market to phaseout earlier than others and also the net impact of banking in delaying release of CFCs to the atmosphere.

Table 2f and Figure 9 show the results of these scenarios. As expected, the history of chlorine abundance from the 50%/50% scenario lies between that of the year-1995 phaseout and that of the year-2000 phaseout. Peak chlorine loading occurs in 1995, and the year when chlorine levels fall below 2 ppb is 2063, about 10 years earlier than in the reference case. Moderate substitution (50% of cuts) with compounds X or Y until the year 2030 give chlorine histories that resemble the reference case without substitution for the first half of the 21st century.

The key result from this scenario is that an earlier partial phaseout of CFCs has distinct advantages: reducing the peak chlorine loading, approaching more rapidly the 2 ppb level (probably eliminating the Antarctic ozone hole), and allowing for substitution without significant increase in the average chlorine levels over the next 50 years. The table below summarizes the peak chlorine loading and the date of 2 ppb chlorine for these scenarios.

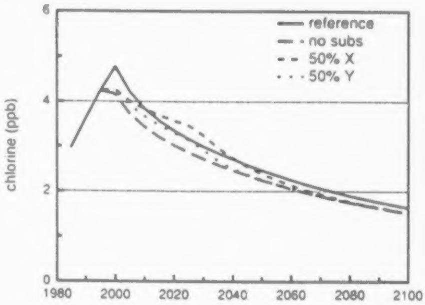


Figure 9. 50/50% cuts in 1995/2000 with subs.

Peak Chlorine Loading and Time to Reach 2 ppb

scenario (phaseout=100% cut)	peak chlorine (ppb)	year when chlorine falls below 2 ppb
2000 phaseout (ref#)	4.78	2073
1995/2000 (50/50%)	4.24	2063

6.6 OBJECTIVE 6. Test the impact of continued use of CH_3CCl_3

This objective was examined by eliminating the emissions of CFCs, CCl_4, and HCFC-22 at the end of year 2000, but continuing CH_3CCl_3 emissions (1990 levels) until the year 2030. Substitution of compound X or Y for a period of 30 years is considered as above, but substitution percentages now refer to a lesser halocarbon budget of 1,220 kt/yr. This scenario recognizes that methyl chloroform is a short-lived halocarbon (about 6 yr) and has properties similar to those of possible CFC substitutes (i.e., compound Y).

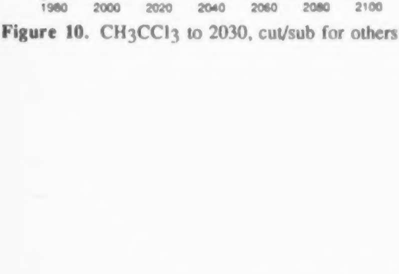


Figure 10. CH_3CCl_3 to 2030, cut/sub for others.

Table 2g and Figure 10 show the results of these scenarios. Compared with the reference scenario, there is no increase in peak chlorine loading and little change in the date at which the atmospheric abundance of chlorine drops below 2 ppb. Substitutions for the phased-out compounds (CFCs, CCl_4 and HCFC-22) show similar properties as in Objective 3, although 100% replacement with compound X maintains near-peak chlorine levels above 4.5 ppb out to the year 2020. Continued use of methyl chloroform is equivalent to substitution with 1,800 kt/yr of compound Y.

When the cuts in CH_3CCl_3 and CFC *production* are simultaneous the *emissions* of CH_3CCl_3 are expected to drop rapidly but those of CFCs will continue at some reduced level as the bank of CFCs is released (see previous discussion). The bank of CFCs as of 1987 (CMA, 1988) would produce only a modest extension of CFC release following a cut in production: emissions would drop to about 30% of production levels in 3 years and continue at an average level of less than 10% out to 20 years. Details of the CFC banking in relation to the timing of the cut in CH_3CCl_3 may slightly affect the peak chlorine loading.

The key point from this scenario is that the phaseout of CH_3CCl_3 production is expected to lead to a rapid cessation of emissions and would result in a relatively rapid decrease of as much as 0.5 ppb in atmospheric chlorine.

6.7 OBJECTIVE 7. Test the impact of current uncertainties in the atmospheric lifetimes of halocarbons;

This objective was examined by increasing or decreasing the recommended atmospheric lifetimes of the halocarbons by 25% for the reference scenario (phaseout of all halocarbons in the year 2000). These limits are extreme (e.g., CFC-11 lifetimes from 45 yr to 75 yr) and cover the most probable range in CFC lifetimes from the best current atmospheric models and from the budget analyses using observations and historical emissions. Assuming that future halocarbon emissions are known, this scenario represents the largest uncertainty in the absolute abundance of atmospheric chlorine from these calculations.

Table 2h and Figure 11 show the results of these scenarios. When halocarbon lifetimes are reduced by 25%, the more rapid destruction of these compounds lowers the peak chlorine concentration by about 0.3 ppb (to 4.5 ppb) and reduces the time to reach 2 ppb chlorine by 20 years (to the year 2053). When halocarbon lifetimes are increased by 25%, the slower destruction of these compounds raises the peak chlorine concentration by about 0.2 ppb (to 5.0 ppb) and increases the time to reach 2 ppb chlorine by 22 years (to the year 2095).

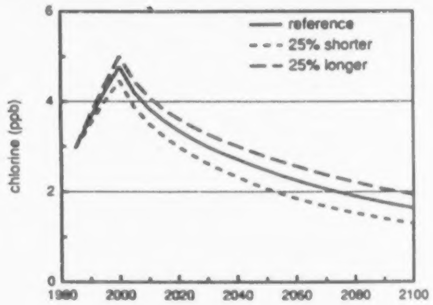


Figure 11. Uncertainty in lifetimes

The key point from these calculations is that the uncertainty in predicting atmospheric chlorine levels in the future, given the history of atmospheric emissions, is not large. More specifically, all of the options to the reference scenario considered above (Objectives 1-6) may need to be shifted up or down, by less than 0.3 ppb, as our understanding and modeling of the atmospheric chemical losses of these compounds improves.

6.8 OBJECTIVE 8. Evaluate the impact of halon emissions on bromine loading.

The atmospheric abundance of bromine in these scenarios is predicted to result from emissions of methyl bromide (CH_3Br) and the halons 1301 (CF_3Br) and 1211 (CF_2ClBr). The other halon specified in the current Montreal Protocol, halon-2402 or $C_2F_4Br_2$, is assumed to be negligible at present and in the future. (The short-lived compound bromoform, $CHBr_3$, is observed occasionally at high concentrations near the ocean surface, but is expected to contribute little to stratospheric bromine.) This scenario is similar to that for chlorine loading and examines the effects of cutting halon emissions to 0%, 20% and 50% of 1985 levels, as well as freezing emissions at their 1990 levels (see Table 3). The assumption here that production and release of halons occurs simultaneously is also incorrect as discussed for CFCs above.

Results are shown in Table 3 and Figure 12. In 1985 the halons 1301 and 1211 together contributed about 3 ppt to the atmospheric abundance of bromine (18 ppt). If their emissions continued at the estimated 1990 production levels then the atmospheric abundance of bromine in the future would approximately triple from about 18 ppt (3 ppt halons) in the year 1985 to 53 ppt (38 ppt halons) by the year 2100.

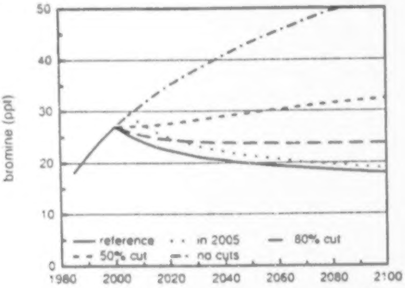


Figure 12. Cut all halocarbons in 2000.

To relate the impact of increases in atmospheric bromine to that of chlorine increases, it would be useful to define a factor relating bromine to chlorine. Such a simple factor is difficult to derive because bromine-catalyzed destruction of ozone is important both globally and in the special environment of the Antarctic ozone hole. Furthermore, much of the loss is coupled to the chlorine abundance as [illegible] above. Currently, one estimate of this factor is about 30 (with a large uncertainty ranging from 10 to 50), and thus the rise in bromine with a freeze on 1990 emissions (increase of 33 ppt) would be about the equivalent of adding 1 ppb of chlorine to the atmosphere.

These calculations, however, assumed that CH_3Br remains constant. There is clear evidence that a substantial fraction of atmospheric CH_3Br is associated with northern continental sources and human activity (e.g., grain fumigation), and thus its concentration may increase in the future.

The key result of these bromine scenarios is that a phaseout or 80% reduction of halon emissions in the near future would stabilize the atmospheric abundance of bromine at about 24 ppt (9 ppt of halons).

7.0 CONCLUSIONS

In order to minimize future ozone depletion, or the potential of damage to the protective stratospheric ozone layer, and to facilitate the elimination of the Antarctic ozone hole it is desirable to:

- phase out production/emission of long-lived halocarbons (CFCs and CCl_4) as soon as possible,
- achieve as great as possible compliance with such a phaseout of CFCs and CCl_4 at the expense of substituting short-lived HCFCs,
- if it becomes necessary to rapidly reduce the peak chlorine loading, make significant cutbacks in the emissions of abundant, short-lived, non-banked halocarbons, particularly CH_3CCl_3,
- phase out in addition the halocarbon substitutes sometime in the middle of the next century if the Antarctic ozone hole is expected to disappear before the end of the next century,
- stabilize the atmospheric bromine concentration at today's level or below.

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Scenarios for Cl and Br

Table 2a. Atmospheric Chlorine (ppb = $1/10^9$) following Cut in all Halocarbon Emissions without Substitutes

year cut	1995 100%	2000 100%#	2005 100%	2000 90%	2000 80%	2000 50%	2000 0%
1985	2.98	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24	4.24
2000	3.71	4.78	4.78	4.78	4.78	4.78	4.78
2005	3.38	4.21	5.28	4.30	4.39	4.65	5.28
2010	3.14	3.84	4.67	3.99	4.15	4.63	5.74
2015	2.95	3.57	4.27	3.78	4.00	4.65	6.17
2020	2.78	3.35	3.97	3.62	3.89	4.69	6.57
2025	2.64	3.16	3.73	3.48	3.79	4.74	6.95
2030	2.51	2.99	3.52	3.35	3.71	4.79	7.30
2035	2.39	2.84	3.33	3.24	3.64	4.84	7.64
2040	2.28	2.71	3.16	3.14	3.58	4.89	7.95
2045	2.18	2.58	3.00	3.05	3.52	4.94	8.25
2050	2.09	2.46	2.86	2.97	3.47	4.99	8.53
2055	2.00	2.35	2.72	2.89	3.42	5.04	8.80
2060	1.92	2.25	2.60	2.81	3.38	5.08	9.05
2065	1.84	2.15	2.48	2.75	3.34	5.12	9.28
2070	1.77	2.06	2.38	2.68	3.30	5.16	9.51
2075	1.70	1.98	2.27	2.63	3.27	5.20	9.72
2080	1.64	1.90	2.18	2.57	3.24	5.24	9.92
2085	1.58	1.83	2.09	2.52	3.21	5.28	10.11
2090	1.53	1.76	2.01	2.47	3.18	5.31	10.28
2095	1.48	1.70	1.93	2.43	3.16	5.35	10.45
2100	1.43	1.64	1.86	2.39	3.13	5.38	10.61

# reference case in all following tables = ref#

Table 2b. Halocarbon Cuts (ref = 100% in 2000) with Substitutes to 2030
(* = +3%/yr growth in substitute)

Atmospheric Chlorine (ppb = 1/10^9)

subs %	none ref#	X 25%	X 50%	X 100%	X *50%	Y 25%	Y 50%	Y 100%	Y *50%
1985	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.31	4.41	4.61	4.43	4.29	4.37	4.53	4.38
2010	3.84	4.01	4.18	4.53	4.25	3.95	4.07	4.30	4.12
2015	3.57	3.79	4.02	4.47	4.16	3.70	3.83	4.09	3.93
2020	3.35	3.61	3.87	4.40	4.12	3.49	3.62	3.90	3.78
2025	3.16	3.45	3.74	4.32	4.12	3.30	3.44	3.72	3.67
2030	2.99	3.30	3.61	4.23	4.15	3.14	3.28	3.56	3.59
2035	2.84	3.07	3.29	3.73	3.67	2.91	2.97	3.09	3.10
2040	2.71	2.86	3.02	3.34	3.30	2.73	2.76	2.81	2.82
2045	2.58	2.69	2.81	3.03	3.00	2.59	2.60	2.63	2.63
2050	2.46	2.54	2.62	2.79	2.76	2.47	2.47	2.48	2.48
2055	2.35	2.41	2.47	2.58	2.57	2.35	2.35	2.36	2.36
2060	2.25	2.29	2.33	2.42	2.40	2.25	2.25	2.25	2.25
2065	2.15	2.18	2.21	2.27	2.26	2.15	2.15	2.15	2.15
2070	2.06	2.09	2.11	2.15	2.14	2.06	2.06	2.06	2.06
2075	1.98	2.00	2.01	2.04	2.04	1.98	1.98	1.98	1.98
2080	1.90	1.91	1.93	1.95	1.94	1.90	1.90	1.90	1.90
2085	1.83	1.84	1.85	1.86	1.86	1.83	1.83	1.83	1.83
2090	1.76	1.77	1.77	1.78	1.78	1.76	1.76	1.76	1.76
2095	1.70	1.70	1.71	1.71	1.71	1.70	1.70	1.70	1.70
2100	1.64	1.64	1.64	1.65	1.65	1.64	1.64	1.64	1.64

Table 2c. Halocarbon Cuts (ref = 100% in 2000) and 100% Substitution for different periods: until 2015, 2030 & 2045

Atmospheric Chlorine (ppb = $1/10^9$)

subs until	none ref#	X 2015	X 2030	X 2045	Y 2030	Y 2045
1985	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.61	4.61	4.61	4.53	4.53
2010	3.84	4.53	4.53	4.53	4.30	4.30
2015	3.57	4.47	4.47	4.47	4.09	4.09
2020	3.35	3.99	4.40	4.40	3.90	3.90
2025	3.16	3.62	4.32	4.32	3.72	3.72
2030	2.99	3.33	4.23	4.23	3.56	3.56
2035	2.84	3.08	3.73	4.14	3.09	3.41
2040	2.71	2.88	3.34	4.04	2.81	3.28
2045	2.58	2.70	3.03	3.94	2.63	3.15
2050	2.46	2.55	2.79	3.43	2.48	2.71
2055	2.35	2.41	2.58	3.05	2.36	2.46
2060	2.25	2.29	2.42	2.75	2.25	2.30
2065	2.15	2.19	2.27	2.51	2.15	2.17
2070	2.06	2.09	2.15	2.32	2.06	2.07
2075	1.98	2.00	2.04	2.16	1.98	1.98
2080	1.90	1.91	1.95	2.03	1.90	1.90
2085	1.83	1.84	1.86	1.92	1.83	1.83
2090	1.76	1.77	1.78	1.83	1.76	1.76
2095	1.70	1.70	1.71	1.75	1.70	1.70
2100	1.64	1.64	1.65	1.67	1.64	1.64

Table 2d. Halocarbon Cuts (ref = 100% in 2000) and Substitution to 2100

Atmospheric Chlorine (ppb = $1/10^9$)

subs %	none ref#	X 25%	X 50%	Y 25%	Y 50%	X&Y 50%
1985	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.31	4.41	4.29	4.37	4.57
2010	3.84	4.01	4.18	3.95	4.07	4.41
2015	3.57	3.79	4.02	3.70	3.83	4.28
2020	3.35	3.61	3.87	3.49	3.62	4.14
2025	3.16	3.45	3.74	3.30	3.44	4.02
2030	2.99	3.30	3.61	3.14	3.28	3.90
2035	2.84	3.17	3.49	2.99	3.13	3.78
2040	2.71	3.04	3.37	2.85	2.99	3.65
2045	2.58	2.92	3.26	2.72	2.86	3.54
2050	2.46	2.80	3.15	2.60	2.75	3.44
2055	2.35	2.70	3.05	2.49	2.64	3.34
2060	2.25	2.60	2.95	2.39	2.53	3.23
2065	2.15	2.51	2.86	2.30	2.44	3.15
2070	2.06	2.42	2.77	2.21	2.35	3.06
2075	1.98	2.34	2.69	2.12	2.27	2.98
2080	1.90	2.26	2.61	2.05	2.19	2.90
2085	1.83	2.19	2.54	1.97	2.12	2.83
2090	1.76	2.12	2.48	1.91	2.05	2.77
2095	1.70	2.06	2.41	1.84	1.98	2.69
2100	1.64	2.00	2.35	1.78	1.92	2.63

Scenarios for Cl and Br

Table 2e. Developed/Undeveloped Scenarios:

100% cut & substitution of all halocarbons, but delay 10% to 20% of cuts (& substitution) by 15 yr.

Atmospheric Chlorine (ppb = $1/10^9$)

cut 2000	100%	90%	90%	90%	80%	80%	80%
cut 2015	ref#	10%	10%	10%	20%	20%	20%
subs	none	none	100%X	100%Y	none	100%X	100%Y
1985	2.98	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.30	4.66	4.59	4.39	4.71	4.64
2010	3.84	3.99	4.62	4.41	4.15	4.71	4.52
2015	3.57	3.78	4.60	4.25	4.00	4.72	4.42
2020	3.35	3.53	4.51	4.06	3.71	4.63	4.21
2025	3.16	3.32	4.43	3.87	3.47	4.54	4.02
2030	2.99	3.14	4.34	3.70	3.28	4.45	3.84
2035	2.84	2.98	3.88	3.25	3.11	4.02	3.41
2040	2.71	2.83	3.51	2.98	2.95	3.69	3.15
2045	2.58	2.69	3.22	2.79	2.81	3.42	2.96
2050	2.46	2.57	2.95	2.61	2.67	3.11	2.74
2055	2.35	2.45	2.72	2.47	2.55	2.86	2.58
2060	2.25	2.34	2.54	2.35	2.44	2.66	2.45
2065	2.15	2.24	2.38	2.24	2.33	2.49	2.33
2070	2.06	2.15	2.25	2.15	2.23	2.35	2.23
2075	1.98	2.06	2.13	2.06	2.14	2.22	2.14
2080	1.90	1.98	2.03	1.98	2.05	2.11	2.05
2085	1.83	1.90	1.94	1.90	1.97	2.01	1.97
2090	1.76	1.83	1.85	1.83	1.89	1.92	1.89
2095	1.70	1.76	1.78	1.76	1.82	1.84	1.82
2100	1.64	1.70	1.71	1.70	1.76	1.77	1.76

Table 2f. Phased Halocarbon Cuts spread over 5 years:
50% cut back in 1995 and remaining 50% in 2000
Substitutes similarly cut back in 2025 and 2030

Atmospheric Chlorine (ppb = $1/10^9$)

subs	ref#	none	50%X	50%Y
1985	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24
2000	4.78	4.16	4.26	4.24
2005	4.21	3.72	4.00	3.92
2010	3.84	3.43	3.83	3.67
2015	3.57	3.20	3.69	3.47
2020	3.35	3.02	3.57	3.30
2025	3.16	2.86	3.46	3.14
2030	2.99	2.71	3.24	2.92
2035	2.84	2.58	2.96	2.67
2040	2.71	2.46	2.73	2.50
2045	2.58	2.35	2.54	2.36
2050	2.46	2.24	2.38	2.25
2055	2.35	2.15	2.25	2.15
2060	2.25	2.05	2.13	2.06
2065	2.15	1.97	2.02	1.97
2070	2.06	1.89	1.93	1.89
2075	1.98	1.82	1.85	1.82
2080	1.90	1.75	1.77	1.75
2085	1.83	1.69	1.70	1.69
2090	1.76	1.63	1.64	1.63
2095	1.70	1.57	1.58	1.57
2100	1.64	1.52	1.52	1.52

Scenarios for Cl and Br

Table 2g. CH_3CCl_3 continued until 2030:

All other halocarbons cut 100% in 2000 with subs until 2030
(* = +3%/yr growth, compounded)

Atmospheric Chlorine (ppb = $1/10^9$)

subs %	none ref#	none 0%	X 25%	X 100%	X *50%	Y 25%	Y 100%	Y *50%
1985	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98
1990	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
1995	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24
2000	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78
2005	4.21	4.48	4.55	4.75	4.63	4.53	4.70	4.60
2010	3.84	4.23	4.34	4.70	4.51	4.30	4.54	4.42
2015	3.57	4.01	4.16	4.62	4.41	4.10	4.36	4.25
2020	3.35	3.81	3.99	4.52	4.33	3.91	4.18	4.11
2025	3.16	3.64	3.83	4.42	4.28	3.73	4.01	3.98
2030	2.99	3.47	3.68	4.31	4.25	3.57	3.86	3.88
2035	2.84	3.05	3.20	3.65	3.61	3.09	3.22	3.23
2040	2.71	2.80	2.90	3.22	3.19	2.81	2.87	2.87
2045	2.58	2.62	2.69	2.92	2.90	2.63	2.65	2.65
2050	2.46	2.48	2.53	2.70	2.68	2.48	2.49	2.49
2055	2.35	2.36	2.40	2.52	2.50	2.36	2.36	2.36
2060	2.25	2.25	2.28	2.36	2.36	2.25	2.25	2.25
2065	2.15	2.15	2.17	2.23	2.23	2.15	2.16	2.16
2070	2.06	2.06	2.08	2.12	2.12	2.06	2.06	2.06
2075	1.98	1.98	1.99	2.02	2.02	1.98	1.98	1.98
2080	1.90	1.90	1.91	1.93	1.93	1.90	1.90	1.90
2085	1.83	1.83	1.84	1.85	1.85	1.83	1.83	1.83
2090	1.76	1.76	1.77	1.78	1.78	1.76	1.76	1.76
2095	1.70	1.70	1.70	1.71	1.71	1.70	1.70	1.70
2100	1.64	1.64	1.64	1.65	1.65	1.64	1.64	1.64

Table 2h. Uncertainty in Halocarbon Lifetimes

Atmospheric Chlorine (ppb = $1/10^9$)

	ref#	25% shorter	25% longer
1985	2.98	2.98	2.98
1990	3.62	3.49	3.71
1995	4.24	4.01	4.40
2000	4.78	4.47	5.01
2005	4.21	3.87	4.46
2010	3.84	3.50	4.10
2015	3.57	3.22	3.82
2020	3.35	2.99	3.61
2025	3.16	2.80	3.43
2030	2.99	2.62	3.27
2035	2.84	2.46	3.13
2040	2.71	2.32	3.00
2045	2.58	2.18	2.88
2050	2.46	2.06	2.76
2055	2.35	1.95	2.66
2060	2.25	1.85	2.56
2065	2.15	1.76	2.46
2070	2.06	1.68	2.37
2075	1.98	1.60	2.29
2080	1.90	1.53	2.21
2085	1.83	1.47	2.13
2090	1.76	1.41	2.06
2095	1.70	1.35	2.00
2100	1.64	1.30	1.93

Table 3. Atmospheric Bromine (ppt = $1/10^{12}$)
Following Cut in all Halocarbon Emissions without Substitutes

year %cut	1995 100%	2000 100%	2005 100%	2000 90%	2000 80%	2000 50%	2000 0%
1985	18.2	18.2	18.2	18.2	18.2	18.2	18.2
1990	21.4	21.4	21.4	21.4	21.4	21.4	21.4
1995	24.4	24.4	24.4	24.4	24.4	24.4	24.4
2000	23.0	27.0	27.0	27.0	27.0	27.0	27.0
2005	22.0	25.3	29.3	25.7	26.0	27.0	29.3
2010	21.2	24.1	27.4	24.7	25.3	27.1	31.3
2015	20.6	23.1	26.0	24.0	24.8	27.3	33.2
2020	20.1	22.4	24.9	23.4	24.5	27.6	35.0
2025	19.7	21.8	24.0	23.0	24.2	27.9	36.6
2030	19.4	21.2	23.3	22.7	24.1	28.3	38.1
2035	19.1	20.8	22.7	22.4	23.9	28.6	39.5
2040	18.9	20.5	22.2	22.2	23.9	29.0	40.9
2045	18.6	20.1	21.7	22.0	23.8	29.3	42.2
2050	18.5	19.9	21.3	21.8	23.8	29.6	43.4
2055	18.3	19.6	21.0	21.7	23.8	30.0	44.5
2060	18.1	19.4	20.7	21.6	23.7	30.3	45.6
2065	18.0	19.2	20.4	21.4	23.7	30.6	46.6
2070	17.8	19.0	20.1	21.3	23.7	30.9	47.6
2075	17.7	18.8	19.9	21.3	23.7	31.2	48.6
2080	17.6	18.6	19.7	21.2	23.7	31.5	49.5
2085	17.5	18.4	19.5	21.1	23.7	31.7	50.3
2090	17.3	18.3	19.2	21.0	23.8	32.0	51.2
2095	17.2	18.1	19.1	20.9	23.8	32.2	51.9
2100	17.1	18.0	18.9	20.9	23.8	32.4	52.7

SECTION D

CHEMICAL KINETICS AND PHOTOCHEMICAL DATA FOR USE IN STRATOSPHERIC MODELING

1.0 Introduction

This compilation (JPL Publication 90-1) is the ninth evaluation of rate constants and photochemical cross sections prepared by the NASA Panel for Data Evaluation. The Panel was established in 1977 for the purpose of providing a critical tabulation of the latest kinetic and photochemical data for use in the modeling of stratospheric processes with particular emphasis on the ozone layer and its possible perturbation by anthropogenic and natural phenomena. Copies of the complete evaluation are available from the Jet Propulsion Laboratory, Documentation Section, 111-116B, California Institute of Technology, Pasadena, California, 91109.

2.0 Basis of the Recommendations

The recommended rate constants and cross sections are based on laboratory measurements. In order to provide recommendations that are as up to date as possible, preprints and written private communications are accepted, but only when it is expected that they will appear as published journal articles. In no cases are rate constants adjusted to fit observations of stratospheric concentrations. The Panel considers the question of consistency of data with expectations based on chemical kinetic theory, and when a discrepancy appears to exist, this fact is pointed out in the accompanying note. The major use of theoretical extrapolation of data is in connection with three-body reactions, in which the required pressure or temperature dependence is sometimes unavailable from laboratory measurements, and can be estimated by use of appropriate theoretical treatment. In the case of important rate constants for which no experimental data are available, the Panel may provide estimates of rate constant parameters based on analogy to similar reactions for which data are available.

3.0 Recent Changes and Current Needs of Laboratory Kinetics

There are approximately forty changes in the rate constant recommendations in the present evaluation, but these are, for the most part, minor. However, some notable improvements have been made in the photochemistry related to Antarctic ozone depletion, as discussed in more detail in later sections. Seventy-two new reactions have been added, many of which are related to the chemistry of hydrochlorofluorocarbons (HCFCs). These latter compounds are being considered as possible industrial alternatives to the fully halogenated chlorofluorocarbons, and the new reactions deal with the chemical fate of the HCFCs in the atmosphere. As in previous evaluations, some reactions thought to be unimportant in the atmosphere are, nevertheless, included for completeness and for possible applications to laboratory studies. A section dealing with laboratory data on heterogeneous chemistry has been added, although this field is not yet fully amenable to evaluation. The table of enthalpy data which, since the last evaluation (JPL Publication 87-41) has been included as an appendix, has been updated and extended.

At the time of publication of the previous evaluation, the phenomenon of Antarctic ozone depletion had focussed intense interest on three areas particularly relevant to polar chemistry: (1)

certain second-order reactions of halogen radicals, such as ClO + ClO and ClO + BrO; (2) heterogeneous chemistry, especially on polar stratospheric clouds; and (3) photochemical kinetics below about 220 K.

In the intervening two years, considerable progress has been made in establishing a database for gas phase (i.e., non-heterogeneous) polar photochemistry. The rates and product distributions of the bimolecular ClO and BrO reactions have been measured more accurately, and there has been further elucidation of the chemistry and photochemistry on the ClO dimer, which is now believed to exist in the atmosphere only in the symmetric form, ClOOCl. Some important gaps remain, however, such as the identity of the photolysis products of ClOOCl.

It is now well-recognized that heterogeneous processes are crucial to stratospheric chemistry in the polar regions, and may play roles in mid-latitudinal regions as well. The heterogeneous chemistry enhances the efficiency of the chlorine catalyzed destruction of stratospheric ozone by converting inactive "reservoir" species such as HCl and $ClONO_2$ to Cl_2 and HOCl. These compounds are photolyzed upon return of sunlight to the polar region, thereby enhancing the levels of active forms of chlorine such as atomic chlorine and the ClO radical. The particles also sequester nitrogen oxides from the stratosphere, in the form of absorbed HNO_3. Thus, the reformation of $ClONO_2$ is suppressed and accelerated ozone destruction occurs during the early Antarctic spring.

Laboratory experiments on heterogeneous chemistry are very complex compared to those for homogeneous chemistry, and experimental techniques are not as well developed. As a consequence, we are not able to make recommendations with the confidence, reliability, and well-defined uncertainty limits that have been characteristic of the homogeneous chemistry. Nonetheless, experiments by several groups have demonstrated a high surface efficiency for key reactions which shift the equilibrium between the chlorine reservoirs and the chemically active forms of chlorine. Quantitative application of the laboratory results to the stratospheric situation is difficult, however, because of uncertainties associated with the nature of the surfaces in question and problems relating to particle microphysics and thermochemistry. These issues are discussed in somewhat more detail in the section on heterogeneous processes.

As mentioned in the previous evaluation, relatively few kinetics measurements have been made below about 220 K, and rate constants for this temperature regime are obtained by extrapolation of data from higher temperatures, using a simple Arrhenius temperature coefficient. The accuracy of such extrapolations is somewhat questionable, however, because several key reactions seem to show non-Arrhenius temperature dependence in this regime. Additional experiments are needed in the 200 K region to verify the accuracy of rate data being used in the models.

3.1 O_x Reactions

The kinetics of the O, O_2, and O_3 system are relatively well-established. The ozone forming reaction, O + O_2 + M, is of fundamental importance in atmospheric chemistry because the extent of ozone destruction is determined by the relative rates of it and competing reactions such as O + O_3, O + NO_2, O + OH, and O + ClO. Thus, additional studies of the O + O_2 + M reaction, or of its relative rate compared to the competing reactions, would be useful at very low temperatures.

3.2 $O(^1D)$ Reactions

The recommended rate coefficients for the $O(^1D)$ reactions correspond to the rate of removal of $O(^1D)$, which includes both chemical reactions and physical quenching of the excited O atoms. Details on the branching ratios are given in the notes in JPL Publication 90-1.

The $O(^1D)$ reactions of 17 fluorine-containing compounds have been added to this review. Most of the compounds are hydrogen-containing fluorocarbons and chlorofluorocarbons that are under consideration as replacements for CFMs. These compounds are reactive toward OH radicals or are photolyzed, so the $O(^1D)$ reactions will generally be minor atmospheric loss processes. On the other hand, SF_6, CF_4, and C_2F_6 do not react with OH and are not readily photolyzed, so the $O(^1D)$ reactions could play an important role in their atmospheric degradation. The small amount of data available on these compounds indicates that the rate coefficients are relatively small, and there is no evidence of significant chemical reaction. The database for most of the new reactions is sparse, and additional measurements of the rate coefficients and branching ratios would be useful.

The kinetic energy or hot atom effects of photolytically generated $O(^1D)$ are probably not important in the atmosphere, although the literature is rich with studies of these processes and with studies of the dynamics of many $O(^1D)$ reactions. The important atmospheric reactions of $O(^1D)$ include: (1) deactivation by major gases, N_2 and O_2, which limit the $O(^1D)$ steady state concentrations; (2) reaction with trace gases, e.g., H_2O, CH_4, and N_2O, which generate radicals; and (3) reaction with long lived trace gases, e.g., HCN, which have relatively slow atmospheric degradation rates. Studies of the $O(^1D)$ reactions with HCN, CF_4, C_2F_6, and SF_6 would contribute to defining the atmospheric lifetimes of these minor species.

3.3 HO_x Reactions

There has been little change in the database for HO_x chemistry since the last evaluation. The OH + HO_2 rate coefficient has been changed slightly to reflect the latest published data. The rate coefficient for the OH + H_2O_2 reaction at 298 K has not been changed, although the Arrhenius parameters have been revised slightly and the data set has been reevaluated to account for revisions in the H_2O_2 UV absorption cross section recommendations. The HO_2 + O_3 reaction rate coefficient remains one of the most significant uncertainties in the HO_x system. High quality data at low temperatures are needed for this key reaction.

3.4 NO_x Reactions

The changes to the database for NO_x reactions are relatively minor. There are new entries for the reactions of OH and HO_2 with NO_3, and for the bimolecular channel of the NO_2 + NO_3 reaction, for which the first direct evidence for the channel giving NO + NO_2 + O_2 is presented. Whether or not this channel actually occurs is still a matter of some controversy, however. There have been some minor updates and revisions to the reactions N + O_2, N + O_3, and NO_2 + O_3.

As noted in the previous evaluation, a few of the important reactions in the NO_x family require additional work. These include the reactions which produce and remove peroxynitric acid, HO_2NO_2. Additional studies of the HO_2 + NO_2 + M recombination are needed, focusing on the temperature dependence of the low pressure limit. In addition, the temperature dependence of the important OH + HO_2NO_2 reaction is still poorly characterized. Additional work on the reactions of NH_2 radicals and subsequent oxidation steps are necessary, particularly under atmospheric conditions.

3.5 Hydrocarbon Oxidation

Our understanding of hydrocarbon oxidation in the atmosphere has improved considerably in the past few years. All hydrocarbons are released at the surface of the earth, and their degradation in the troposphere is initiated by reaction with OH (and with ozone in the case of olefins). Depending on their reactivity with OH, only a fraction of the surface flux of hydrocarbons is transported to the stratosphere, where their oxidation serves as a source of water vapor. In addition, the reaction of atomic chlorine with these hydrocarbons (mainly CH_4) constitutes one of the major sink mechanisms for active chlorine. Even though CH_4 is the predominant hydrocarbon in the stratosphere, we have included in this evaluation certain reactions of a few heavier hydrocarbon species.

In the stratosphere, CH_4 oxidation leads initially to formation of CH_3, which immediately is converted to CH_3O_2. Some of the subsequent chemistry is not clear, primarily because the key reaction of CH_3O_2 with HO_2 is not well-characterized, even though there have been three new studies of this reaction. Not all the products of the reaction have been identified. Some of the recent work suggests that, in addition to CH_3OOH, CH_2O is also formed. Our understanding of the reaction between OH and CH_3OOH has improved significantly since the last evaluation. Even though the rate constants for some of the reactions mentioned above are not well-defined, the effects of these uncertainties on stratospheric ozone perturbation are negligible.

One area of hydrocarbon oxidation which has seen a great deal of improvement is that of product analysis. However, some additional work may be required to measure branching ratios for reactions such as $CH_3O_2 + CH_3O_2$ and $CH_3O_2 + HO_2$.

The rates of the reactions of higher hydrocarbons with OH are sufficiently well-measured to permit their rate of transport to the stratosphere to be calculated. However, the oxidation scheme for these hydrocarbons has not been fully elucidated. In most cases, it is expected that the radicals formed from the initial OH or Cl attack will follow courses analogous to that of CH_3, and ultimately lead to CO. In this evaluation, we have included some, but not all, of the reactions in the oxidation of ethane to CO. We have also added the reactions of OH with CH_3OH and C_2H_5OH, the most abundant alcohols in the stratosphere.

3.6 Halogen Chemistry

The kinetics database for halogen reactions has shown significant expansion and improvement since the previous evaluation. It now contains rate coefficients for the reaction of OH with a large number of potential alternatives to the fully halogenated CFCs, [nine hydrochlorofluorocarbons (HCFCs) and eleven hydrofluorocarbons (HFCs)]. The chemistry of these species in the troposphere is controlled by their reactions with OH whereby a hydrogen atom is abstracted and a hydrocarbon radical produced. There are now also upper limits for the rate constants for the reactions of OH with four brominated fully halogenated halocarbons (Halons). Other new entries include several reactions of Cl_2O_2, the dimer formed by recombination of two ClO radicals, several reactions of OClO, and reactions of NO_3 with several bromine species. The important recombination of ClO radicals to produce Cl_2O_2 has now been directly studied under polar stratospheric conditions and found to be significantly slower than had been believed on the basis of earlier studies. The bimolecular channels for the ClO + ClO reaction have been shown to be unimportant under the same conditions. The important BrO + ClO reaction has now been directly studied under polar stratospheric conditions, and has been found to proceed through three reaction channels for which reliable temperature dependent rate expressions have been derived. With these expansions and improvements, the kinetics database for homogeneous reactions of halogen species appears to be relatively well established.

3.7 SO_x Reactions

The database on homogeneous sulfur chemistry has seen only minor changes in the recommendations for the reactions that were included in the previous evaluation. However, this section has been expanded significantly to include many reactions that are important in the atmospheric oxidation of reduced compounds of natural and anthropogenic origin. These new entries include the reactions of OH and NO_3 radicals with simple organic sulfides, as well as several reactions representing the oxidation of the radical products CH_3S and CH_3SO. There have not been significant improvements in our understanding of the oxidation of SO_2 into sulfuric acid, although there have been several direct measurements of the $HOSO_2$ intermediate. There is still a need for further information on the atmospheric reactivity of this species and, perhaps, even on reactions involving its possible complexes with O_2 or H_2O. Along these same lines, further information on the reactions of SO_3 with other atmospheric species is needed to assess the competition of these reactions with SO_3 hydrolysis. Finally, further details have been provided on the mechanism for CS_2 atmospheric oxidation. The database has also been expanded to include the reactions of NO_3 with both OCS and CS_2.

3.8 Metal Chemistry

Sodium is deposited in the upper atmosphere by meteors along with larger amounts of silicon, magnesium, and iron; comparable amounts of aluminum, nickel, and calcium; and smaller amounts of potassium, chromium, manganese, and other elements. The interest is greatest in the alkali metals because they form the least stable oxides and thus free atoms can be regenerated through photolysis and reactions with O and O_3. The other meteoric elements are expected to form more stable oxides.

The total flux of alkali metals through the atmosphere is relatively small, e.g., one or two orders of magnitude less than CFCs. Therefore extremely efficient catalytic cycles are required in order for Na to have a significant effect on stratospheric chemistry. There are no measurements of metals or metal compounds in the stratosphere which indicate a significant role.

It has been proposed that the highly polar metal compounds may polymerize to form clusters and that the stratospheric concentrations of free metal compounds are too small to play a significant role in the chemistry.

Some studies have shown that the polar species NaO and NaOH associate with abundant gases such as O_2 and CO_2 with very fast rates in the atmosphere. It has been proposed that reactions of this type will lead to the production of clusters with many molecules attached to the sodium compounds. Photolysis is expected to compete with the association reactions and to limit the cluster concentrations in daylight. If atmospheric sodium does form large clusters, it is unlikely that Na species can have a significant role in stratospheric ozone chemistry. In order to assess the importance of these processes, data are needed on the association rates and the photolysis rates involving the cluster species.

3.9 Photochemical Cross Sections

Absorption spectra of a few species which have highly structured spectra have now been included in graphical, as well as tabular, form (JPL Publication 90-1). These figures are only a guide to the spectra, and should not be used for quantitative purposes, because the measured cross sections may be resolution dependent. Spectra of the haloethanes have been included to show the shape of the spectra.

The absorption cross sections of the Cl_2O_2 molecule formed by the association of two ClO radicals have also been included. The quantum yield for the photo-dissociation of the dimer is believed to be unity. The products have not been established, although it is probable that Cl + ClOO are produced with unit efficiency.

The cross sections for many halocarbons which are expected to be replacements for the chlorofluoromethanes have been included and the cross sections for bromocarbons updated.

The temperature dependence of the absorption cross sections of species such as HO_2NO_2 and H_2O_2 in the 300 nm region may be important. We have thus included the measured temperature dependence for H_2O_2 in this latest evaluation. Data on HO_2NO_2 are not available. In the case of haloethanes, there are large discrepancies between the available sets of data and, therefore, we have not included these results. Additional laser experiments are needed.

The recommendation for the wavelength dependence of the $0(^1D)$ quantum yield in ozone photolysis has been modified to represent more closely the results obtained from laser photolysis experiments. The latter have better resolution than the earlier monochromator measurements, and thus are believed to reproduce the fall-off behavior more accurately. However, the laser results are not in complete agreement, particularly at the longest wavelengths. Furthermore, the temperature dependence of the O (^1D) quantum yield has not been measured using laser sources, and it was necessary in this evaluation to use monochromator results for the temperature dependence. The laser experiments should be performed.

4.0 Atmospheric Chemistry

4.1 Overview

The ozone content of earth's atmosphere can be considered to exist in three distinct regions; the troposphere, stratosphere, and mesosphere. The unpolluted troposphere contains small amounts of ozone, which come from both downward transport from the stratosphere and from in situ photochemical production. The chemistry of the global troposphere is complex, with both homogeneous and heterogeneous (e.g., rain-out) processes playing important roles. The homogeneous chemistry is governed by coupling between the carbon, nitrogen, hydrogen, and oxygen systems and can be considered to be more complex than the chemistry of the stratosphere, due to the presence of higher hydrocarbons, long photochemical relaxation times, higher total pressures, and the high relative humidity which may affect the reactivity of certain key species such as HO_2. Significant progress is being made in understanding the coupling among the different chemical systems, especially the mechanism of methane oxidation which partially controls the odd hydrogen budget. This is an important development, as reactions of the hydroxyl radical are the primary loss mechanism for compounds containing C-H (CH_4, CH_3Cl, CHF_2Cl, etc.) or C=C (C_2Cl_4, C_2HCl_3, C_2H_4, etc.), thus limiting the fraction transported into the stratosphere.

The stratosphere is the region of the atmosphere where the bulk of the ozone resides, with the concentration reaching a maximum value of about 5×10^{12} molecule cm^{-3} at an altitude of ~25 km. Ozone in the stratosphere is removed predominantly by catalytic processes, but assignment of the relative importance of different catalytic cycles and the prediction of their future impact are dependent on a detailed understanding of chemical reactions which form, remove and interconvert the catalytic species. A model calculation of stratospheric composition may include some 150 chemical reactions and photochemical processes, which vary greatly in their importance in controlling the density of ozone. Laboratory measurements of the rates of these reactions have progressed rapidly in recent years, and have given us a basic understanding of the processes involved, particularly in the upper stratosphere. Despite the basically sound understanding of overall stratospheric chemistry which presently exists, much remains to be done to quantify errors, to identify reaction channels positively, and to measure reaction rates both under conditions corresponding to the lower stratosphere (~210 K, ~75 torr), as well as the top of the stratosphere (~270 K, ~1 torr). As previously mentioned, Antarctic conditions require the consideration of even lower temperatures.

The chemistry of the upper stratosphere, i.e. 30-50 km, is thought to be reasonably well defined, although there appear to be some significant differences between the predicted and observed chemical composition of this region of the atmosphere, which may be due to inaccurate

rate data or missing chemistry. In this region, the composition of the atmosphere is predominantly photochemically controlled, and the photolytic lifetimes of temporary reservoir species such as HOCl, HO_2NO_2, $ClONO_2$, N_2O_5 and H_2O_2 are short; and, hence, they play a minor role. Thus, the important processes above 30 km all involve atoms and small molecules. The majority of laboratory studies of these reactions have been carried out under the conditions of pressure and temperature which are encountered in the upper stratosphere, and their overall status appears to be good. No significant changes in rate coefficients for the key reactions, such as $Cl + O_3$, NO + ClO, $NO + O_3$, etc., have occurred in the last few years. Historically, a major area of concern in the chemistry of the upper stratosphere has involved the reaction between HO and HO_2 radicals, which has had considerable uncertainty in the rate constant. This HO_x termination reaction plays an important role in determining the absolute concentrations of HO and HO_2, and since HO plays a central role in controlling the catalytic efficiencies of both NO_x and ClO_x, it is a reaction of considerable importance. The uncertainty in the rate coefficient for the reaction is thought to be about a factor of 1.3 to 1.8 over the range of atmospheric conditions. It should be noted that the $HO + H_2O_2$, $HO + HNO_3$ and $HO + HO_2NO_2$ reactions have little effect on controlling the HO_x concentrations above 30 km. For reactions such as O + HO and $O + HO_2$, which control the HO_x radical partitioning above 40 km, the database can be considered to be quite good.

One area in which additional studies may be needed is that of excited state chemistry, i.e., studies to determine whether electronic or vibrational states of certain atmospheric constituents may be more important than hitherto recognized. Possible examples are O_2^*, O_3^*, HO^*, or N_2^*.

The chemistry of the lower stratosphere is quite complex, with significant coupling between the HO_x, NO_x and ClO_x families. In this region of the atmosphere (15-30 km), both dynamics and photochemistry play key roles in controlling the trace gas distributions. It is also within this region that the question of the pressure and temperature dependences of the rate coefficients is most critical, due to the low temperatures (210 K and lower) and the high total pressures (30-200 torr).

4.2 Heterogeneous Effects

A continuing question in stratospheric modeling is whether or not aerosols perturb the homogeneous chemistry to a significant degree. As mentioned earlier, this question has assumed much greater importance in connection with the role of polar stratospheric clouds in Antarctic chemistry. On a global scale, effects have been suggested through the following processes:

(1) Surface catalysis of chemical reactions.

(2) Production or removal of active species.

(3) Effects of aerosol precursors such as SO_2.

In NASA Reference Publications 1010 and 1049, processes 1 and 2 above were discussed in general terms. It was shown that, with a few possibly significant exceptions, surface catalysis of chemical reactions is not expected to compete with the rates of homogeneous gas phase reactions. The essential reason is that the frequency of collision of a gas phase molecule with the aerosol surface is typically of the order of 10^{-5} sec^{-1}, whereas most of the key gas phase reactions occur with much greater frequency, for example, conversion of atomic chlorine to HCl by the $Cl + CH_4$ reaction (10^{-2} sec^{-1}). Thus, even in the unlikely case of unit reaction efficiency on the aerosol surface the heterogeneous process cannot be significant. Possible exceptions occur for reactions which are extremely slow in the gas phase, such as hydrolysis of an anhydride, as in the reaction $N_2O_5 + H_2O \rightarrow 2HNO_3$. There remains some uncertainty with regard to the role of these latter processes.

It was also shown in NASA Publications 1010 and 1049 that there is no evidence that aerosols serve as significant sources or sinks of the major active species such as chlorine compounds. However, it has been suggested that dust particles of meteoritic origin may scavenge metallic atoms and ions and, in particular, may remove Na diffusing from the mesosphere in the form of absorbed NaOH or Na_2SO_4.

Although it appears that aerosols do not greatly perturb the ambient concentrations of active species through direct interaction with the surfaces, the aerosol precursors may significantly perturb the stratospheric cycles through removal of species such as OH radicals. For example, a large injection of SO_2, such as that which occurred in the El Chichon eruption, has the potential of significantly depleting HO_x radical concentrations. It must be reiterated, however, that recent studies of the mechanism of SO_2 oxidation have shown that OH plays a catalytic role, and, therefore, the process does not result in a net loss of OH from the system.

The effects of aerosols on the radiation field and on the temperature may also need to be considered. These effects are probably small, however.

There are two problems with regard to detecting the effects of aerosol injections such as that following the El Chichon eruption. One is that no adequate baseline exists for the unperturbed atmosphere, and therefore a given observation cannot unambiguously be assigned to the enhanced presence of the aerosol loading. A second problem is that, as already discussed, the effects are expected to be subtle and probably of small magnitude. Thus, in spite of large changes that may occur in the aerosol content of the lower stratosphere, effects on the chemical balance will be difficult to detect.

5.0 Rate Constant Data

In Table 1 (Rate Constants for Second Order Reactions) the reactions are grouped into the classes O_x, $O(^1D)$, HO_x, NO_x, Hydrocarbon Reactions, ClO_x, BrO_x, FO_x, and SO_x. The data in Table 2 (Rate Constants for Three-Body Reactions), while not grouped by class, are presented in the same order as the bimolecular reactions. Further, the presentation of photochemical cross section data follows the same sequence.

5.1 Bimolecular Reactions

Some of the reactions in Table 1 are actually more complex than simple two-body reactions. To explain the anomalous pressure and temperature dependences occasionally seen in reactions of this type, it is necessary to consider the bimolecular class of reactions in terms of two subcategories, direct (concerted) and indirect (non-concerted) reactions.

A direct or concerted bimolecular reaction is one in which the reactants A and B proceed to products C and D without the intermediate formation of an AB adduct which has appreciable bonding, i.e., no stable A-B molecule exists, and there is no reaction intermediate other than the transition state of the reaction, $(AB)^\#$.

$$A + B \rightarrow (AB)^\# \rightarrow C + D$$

The reaction of OH with CH_4 forming $H_2O + CH_3$ is an example of a reaction of this class.

Very useful correlations between the expected structure of the transition state $(AB)^\#$ and the A-factor of the reaction rate constant can be made, especially in reactions which are constrained to follow a well-defined approach of the two reactants in order to minimize energy requirements in the making and breaking of bonds. The rate constants for these reactions are well represented by the Arrhenius expression k = A exp(-E/RT) in the 200-300 K temperature range. These rate constants are not pressure dependent.

The indirect or non-concerted class of bimolecular reactions is characterized by a more complex reaction path involving a potential well between reactants and products, leading to a bound adduct (or reaction complex) formed between the reactants A and B:

$$A + B \rightarrow (AB)^* \rightarrow C + D$$

The intermediate $(AB)^*$ is different from the transition state $(AB)^\#$, in that it is a bound molecule which can, in principle, be isolated. (Of course, transition states are involved in all of the above reactions, both forward and backward, but are not explicitly shown.) An example of this reaction type is ClO + NO, which normally produces Cl + NO_2 as a bimolecular product, but which undoubtedly involves ClONO (chlorine nitrite) as an intermediate. This can be viewed as a chemical activation process forming $(ClONO)^*$ which decomposes to the ultimate products, Cl + NO_2. Reactions of the non-concerted type can have a more complex temperature dependence, can exhibit a pressure dependence if the lifetime of $(AB)^*$ is comparable to the rate of collisional deactivation of $(AB)^*$. This arises because the relative rate at which $(AB)^*$ goes to products C + D vs. reactants A + B is a sensitive function of its excitation energy. Thus, in reactions of this type, the distinction between the bimolecular and termolecular classification becomes less meaningful, and it is especially necessary to study such reactions under the temperature and pressure conditions in which they are to be used in model calculations.

The rate constant tabulation for second-order reactions (Table 1) is given in Arrhenius form: $k(T) = A \exp((-E/R)(1/T))$ and contains the following information:

(1) Reaction stoichiometry and products (if known). The pressure dependences are included, where appropriate.

(2) Arrhenius A-factor.

(3) Temperature dependence and associated uncertainty ("activation temperature" $E/R \pm \Delta E/R$).

(4) Rate constant at 298 K.

(5) Uncertainty factor at 298 K.

5.2 Termolecular Reactions

Rate constants for 3rd order reactions (Table 2) of the type $A + B \leftrightarrow (AB)^* \rightarrow AB$ are given in the form

$$k_o(T) = k_o^{300}(T/300)^{-n} \text{ cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$$

(where the value is suitable for air as the third body), together with the recommended value of n. Where pressure fall-off corrections are necessary, an additional entry gives the limiting high pressure rate constant in a similar form:

$$k_\infty(T) = k_\infty^{300}(T/300)^{-m} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$$

To obtain the effective second-order rate constant for a given condition of temperature and pressure (altitude), the following formula is used:

$$k(Z) = k(M,T) = (\{k_o(T)[M]\}/\{1+k_o(T)[M]/k_\infty(T)\})0.6^{\frac{1}{\alpha}}$$

where

$$\alpha = 1 + \{\log_{10}(k_o(T)[M]/k_\infty(T))\}^2$$

The fixed value 0.6 which appears in this formula fits the data for all listed reactions adequately, although in principle this quantity may be different for each reaction.

Thus, a compilation of rate constants of this type requires the stipulation of the four parameters, $k_o(300)$, n, $k_\infty(300)$, and m. These can be found in Table 2. The discussion that follows outlines the general methods we have used in establishing this table.

5.2.1 Low-Pressure Limiting Rate Constant [$k^x{}_o(T)$]

Troe (J. Chem. Phys. 66, 4745 (1977)) has described a simple method for obtaining low-pressure limiting rate constants. In essence this method depends on the definition:

$$k^x{}_o(T) = \beta_x k^x{}_{o,sc}(T)$$

Here sc signifies "strong" collisions, x denotes the bath gas, and β_x is an efficiency parameter ($0 < \beta_x < 1$), which provides a measure of energy transfer.

The coefficient β_x is related to the average energy transferred in a collision with gas x, $<\Delta E>_x$, via:

$$\beta_x/(1-\beta_x{}^{0.5}) = <\Delta E>_x/F_E kT$$

Notice that $<\Delta E>_x$ is quite sensitive to β. F_E is the correction factor of the energy dependence of the density of states (a quantity of the order of 1.1 for most species of stratospheric interest).

For many of the reactions of possible stratospheric interest reviewed here, there exist data in the low-pressure limit (or very close thereto), and we have chosen to evaluate and unify this data by calculating $k^x{}_{o,sc}(T)$ for the appropriate bath gas x and computing the value of β_x corresponding to the experimental value. A recent compilation (Patrick and Golden, Int. J. Chem. Kinet. 15, 1189 (1983)) gives details for many of the reactions considered here.

From the β_x values (most of which are for N_2, i.e., β_{N2}), we compute $<\Delta E>_x$ according to the above equation. Values of $<\Delta E>_{N2}$ of approximately 0.3 - 1.0 kcal mole^{-1} are generally expected. If multiple data exist, we average the values of $<\Delta E>_{N2}$ and recommend a rate constant corresponding to the β_{N2} computed in the equation above.

Where no data exist we have estimated the low-pressure rate constant by taking $\beta_{N2} = 0.3$ at T = 300 K, a value based on those cases where data exist.

5.2.2 Temperature Dependence of Low-Pressure Limiting Rate Constants: n

The value of n recommended here comes from a calculation of $<\Delta E>_{N2}$ from the data at 300 K, and a computation of $\beta_{N2}(200\ K)$ assuming that $<\Delta E>_{N2}$ is independent of temperature in this range. This $\beta_{N2}(200\ K)$ value is combined with the computed value of $k_{o,sc}(200\ K)$ to give the expected value of the actual rate constant at 200 K. This latter in combination with the value at 300 K yields the value of n.

This procedure can be directly compared with measured values of $k_0(200\ K)$ when those exist. Unfortunately, very few values at 200 K are available. There are often temperature-dependent studies, but some ambiguity exists when one attempts to extrapolate these down to 200 K. If data are to be extrapolated beyond the measured temperature range, a choice must be made as to the functional form of the temperature dependence. There are two general ways of expressing the temperature dependence of rate constants. Either the Arrhenius expression $k_0(T) = A\exp(-E/RT)$ or the form $k_0(T) = A'T^{-n}$ is employed. Since neither of these extrapolation techniques is soundly based, and since they often yield values that differ substantially, we have used the method explained earlier as the basis of our recommendations.

5.2.3 High-Pressure Limit Rate Constants, $k_\infty(T)$

High-pressure rate constants can often be obtained experimentally, but those for the relatively small species of atmospheric importance usually reach the high-pressure limit at inaccessibly high pressures. This leaves two sources of these numbers, the first being guesses based upon some model, and the second being extrapolation of fall-off data up to higher pressures. Stratospheric conditions generally render reactions of interest much closer to the low-pressure limit, and thus are fairly insensitive to the high-pressure value. This means that while the extrapolation is long, and the value of $k_\infty(T)$ not very accurate, a "reasonable guess" of $k_\infty(T)$ will then suffice. In some cases we have declined to guess since the low-pressure limit is effective over the entire range of stratospheric conditions.

5.2.4 Temperature Dependence of High-Pressure Limit Rate Constants: m

There are very little data upon which to base a recommendation for values of m. Values in Table 2 are estimated, based on models for the transition state of bond association reactions and whatever data are available.

5.2.5 Isomer Formation

A particular problem with association reactions arises when there are easily accessible isomeric forms of the molecule AB. In this situation, if the laboratory measurement of the rate constant is accomplished by following the disappearance of reactants, the value ascertained may be the sum of two or more processes that should be measured and tabulated independently. A specific example of such a case is found in Table 2 for the reactions of Cl-atoms with NO_2. These reactants may come together to form either $ClNO_2$ or ClONO. Whether or not isomer formation, such as discussed above, is important depends on the relative stability of the possible products. At the moment the only case that we are sure about is the above example. In the past however, there was some thought that data on the reaction between ClO radicals and NO_2 could be understood only in terms of the formation of both chlorine nitrate ($ClONO_2$) and other isomers (ClOONO, OClONO). Experiments have shown that this is not the case and that chlorine nitrate is the sole product.

There are many other possibilities for isomer formation in the reactions listed in Table 2. Even for reactions where no mention is made of isomers, because we felt that they could not contribute under atmospheric conditions, extrapolation to higher pressures and lower temperatures should be done with the possibilities kept in mind.

5.3 Uncertainty Estimates

For second-order rate constants in Table 1, an estimate of the uncertainty at any given temperature may be obtained from the following expression:

$$f(T) = f(298)\exp((\Delta E/R)(1/T - 1/298))$$

An upper or lower bound (corresponding approximately to one standard deviation) of the rate constant at any temperature T can be obtained by multiplying or dividing the value of the rate constant at that temperature by the factor f(T). The quantities f(298) and $\Delta E/R$ are, respectively, the uncertainty in the rate constant at 298 K and in the Arrhenius temperature coefficient, as listed in Table 1. This approach is based on the fact that rate constants are almost always known with minimum uncertainty at room temperature. The overall uncertainty normally increases at other temperatures, because there are usually fewer data and it is almost always more difficult to make measurements at other temperatures. It is important to note that the uncertainty at a temperature T cannot be calculated from the expression $\exp(\Delta E/RT)$. The above expression for f(T) must be used to obtain the correct result.

The uncertainty represented by f(298) is normally symmetric; i.e., the rate constant may be greater than or less than the central value, k(298), by the factor f(298). In a few cases in Table 1 asymmetric uncertainties are given in the temperature coefficient.

For these cases, the factors by which a rate constant are to be multiplied or divided to obtain, respectively, the upper and lower limits are not equal, except at 298 K where the factor is simply f(298K). Explicit equations are given below for the case where the temperature dependence is (E/R +a, -b):

For T > 298K, multiply by the factor

$$f(298K) \times e^{[a \times (1/298 - 1/T)]}$$

and divide by the factor

$$f(298K) \times e^{[b \times (1/298 - 1/T)]}.$$

For T < 298K, multiply by the factor

$$f(298K) \times e^{[b \times (1/T - 1/298)]}$$

and divide by the factor

$$f(298K) \times e^{[a \times (1/T - 1/298)]}.$$

For three-body reactions (Table 2) a somewhat analogous procedure is used. Uncertainties expressed as increments to k_0 and k_∞ are given for these rate constants at room temperature. The additional uncertainty arising from the temperature extrapolation is expressed as an uncertainty in the temperature coefficients n and m.

The assigned uncertainties represent the subjective judgment of the Panel. They are not determined by a rigorous, statistical analysis of the database, which generally is too limited to permit such an analysis. Rather, the uncertainties are based on a knowledge of the techniques, the difficulties of the experiments, and the potential for systematic errors. There is obviously no way to quantify these "unknown" errors. The spread in results among different techniques for a given reaction may provide some basis for an uncertainty, but the possibility of the same, or compensating, systematic errors in all the studies must be recognized. Furthermore, the probability distribution may not follow the normal, Gaussian form. For measurements subject to large systematic errors, the true rate constant may be much further from the recommended value than would be expected based on a Gaussian distribution with the stated uncertainty. As an example, the recommended rate constants for the reactions HO_2 + NO and Cl + $ClONO_2$ have changed by factors of 30-50, occurrences which could not have been allowed for with any reasonable values of σ in a Gaussian distribution.

5.4 Units

The rate constants are given in units of concentration expressed as molecules per cubic centimeter and time in seconds. Thus, for first-, second-, and third-order reactions the units of k are s^{-1}, cm^3 $molecule^{-1}$ s^{-1}, and cm^6 $molecule^{-2}$ s^{-1}, respectively. Cross sections are expressed as cm^2 $molecule^{-1}$, base e.

Chemical Kinetics and Photochemical Data

Table 1. Rate Constants for Second Order Reactions[a]

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
		O_x Reactions		
$O + O_2 \xrightarrow{M} O_3$	(See Table 2)			
$O + O_3 \rightarrow O_2 + O_2$	8.0×10^{-12}	2060±250	8.0×10^{-15}	1.15
		$O(^1D)$ Reactions		
$O(^1D) + N_2O \rightarrow N_2 + O_2$	4.9×10^{-11}	0±100	4.9×10^{-11}	1.3
$\rightarrow NO + NO$	6.7×10^{-11}	0±100	6.7×10^{-11}	1.3
$O(^1D) + H_2O \rightarrow OH + OH$	2.2×10^{-10}	0±100	2.2×10^{-10}	1.2
$O(^1D) + CH_4 \rightarrow OH + CH_3$	1.4×10^{-10}	0±100	1.4×10^{-10}	1.2
$\rightarrow H_2 + CH_2O$	1.4×10^{-11}	0±100	1.4×10^{-11}	1.2
$O(^1D) + H_2 \rightarrow OH + H$	1.0×10^{-10}	0±100	1.0×10^{-10}	1.2
$O(^1D) + N_2 \rightarrow O + N_2$	1.8×10^{-11}	-(110±100)	2.6×10^{-11}	1.2
$O(^1D) + N_2 \xrightarrow{M} N_2O$	(See Table 2)			
$O(^1D) + O_2 \rightarrow O + O_2$	3.2×10^{-11}	-(70±100)	4.0×10^{-11}	1.2
$O(^1D) + CO_2 \rightarrow O + CO_2$	7.4×10^{-11}	-(120±100)	1.1×10^{-10}	1.2
$O(^1D) + O_3 \rightarrow O_2 + O_2$	1.2×10^{-10}	0±100	1.2×10^{-10}	1.3
$\rightarrow O_2 + O + O$	1.2×10^{-10}	0±100	1.2×10^{-10}	1.3
$O(^1D) + HCl \rightarrow$ products	1.5×10^{-10}	0±100	1.5×10^{-10}	1.2
$O(^1D) + HF \rightarrow OH + F$	1.4×10^{-10}	0±100	1.4×10^{-10}	2.0
$O(^1D) + HBr \rightarrow$ products	1.5×10^{-10}	0±100	1.5×10^{-10}	2.0
$O(^1D) + Cl_2 \rightarrow$ products	2.8×10^{-10}	0±100	2.8×10^{-10}	2.0
$O(^1D) + CCl_4 \rightarrow$ products	3.3×10^{-10}	0±100	3.3×10^{-10}	1.2
$O(^1D) + CFCl_3 \rightarrow$ products	2.3×10^{-10}	0±100	2.3×10^{-10}	1.2
$O(^1D) + CF_2Cl_2 \rightarrow$ products	1.4×10^{-10}	0±100	1.4×10^{-10}	1.3
$O(^1D) + CF_4 \rightarrow CF_4 + O$	-	-	$<1.8\times10^{-13}$	-
$O(^1D) + CCl_2O \rightarrow$ products	3.6×10^{-10}	0±100	3.6×10^{-10}	2.0

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$O(^1D) + CFClO \rightarrow$ products	1.9×10^{-10}	0±100	1.9×10^{-10}	2.0
$O(^1D) + CF_2O \rightarrow$ products	7.4×10^{-11}	0±100	7.4×10^{-11}	2.0
$O(^1D) + NH_3 \rightarrow OH + NH_2$	2.5×10^{-10}	0±100	2.5×10^{-10}	1.3
$O(^1D) + CHFCl_2 \rightarrow$ products	1.9×10^{-10}	0±100	1.9×10^{-10}	1.3
$O(^1D) + CHF_2Cl \rightarrow$ products	9.5×10^{-11}	0±100	9.5×10^{-11}	1.3
$O(^1D) + CHF_3 \rightarrow$ products	8.4×10^{-12}	0±100	8.4×10^{-12}	5.0
$O(^1D) + CH_2F_2 \rightarrow$ products	9×10^{-11}	0±100	9×10^{-11}	3.0
$O(^1D) + CH_3F \rightarrow$ products	1.4×10^{-10}	0±100	1.4×10^{-10}	2.0
$O(^1D) + CHCl_2CF_3 \rightarrow$ products	2.2×10^{-10}	0±100	2.2×10^{-10}	2.0
$O(^1D) + CHFClCF_3 \rightarrow$ products	1×10^{-10}	0±100	1×10^{-10}	3.0
$O(^1D) + CHF_2CF_3 \rightarrow$ products	5×10^{-11}	0±100	5×10^{-11}	3.0
$O(^1D) + CH_2ClCF_2Cl \rightarrow$ products	1.6×10^{-10}	0±100	1.6×10^{-10}	2.0
$O(^1D) + CH_2ClCF_3 \rightarrow$ products	1.5×10^{-10}	0±100	1.5×10^{-10}	2.0
$O(^1D) + CH_2FCF_3 \rightarrow$ products	1×10^{-10}	0±100	1×10^{-10}	3.0
$O(^1D) + CH_3CFCl_2 \rightarrow$ products	1.5×10^{-10}	0±100	1.5×10^{-10}	3.0
$O(^1D) + CH_3CF_2Cl \rightarrow$ products	1.4×10^{-10}	0±100	1.4×10^{-10}	2.0
$O(^1D) + CH_3CF_3 \rightarrow$ products	1.0×10^{-10}	0±100	1.0×10^{-10}	3.0
$O(^1D) + CH_3CHF_2 \rightarrow$ products	1×10^{-10}	0±100	1×10^{-10}	3.0
$O(^1D) + C_2F_6 \rightarrow O + C_2F_6$	-	-	$<2\times10^{-13}$	-
$O(^1D) + SF_6 \rightarrow$ products	-	-	$<4.5\times10^{-14}$	-
		HO_x Reactions		
$H + O_2 \xrightarrow{M} HO_2$	(See Table 2)			
$H + O_3 \rightarrow OH + O_2$	1.4×10^{-10}	470±200	2.9×10^{-11}	1.25
$H + HO_2 \rightarrow$ products	8.1×10^{-11}	0±200	8.1×10^{-11}	1.3

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$O + OH \rightarrow O_2 + H$	2.2×10^{-11}	-(120±100)	3.3×10^{-11}	1.2
$O + HO_2 \rightarrow OH + O_2$	3.0×10^{-11}	-(200±100)	5.9×10^{-11}	1.2
$O + H_2O_2 \rightarrow OH + HO_2$	1.4×10^{-12}	2000±1000	1.7×10^{-15}	2.0
$OH + HO_2 \rightarrow H_2O + O_2$	4.8×10^{-11}	-(250±200)	1.1×10^{-10}	1.3
$OH + O_3 \rightarrow HO_2 + O_2$	1.6×10^{-12}	940±300	6.8×10^{-14}	1.3
$OH + OH \rightarrow H_2O + O$	4.2×10^{-12}	240±240	1.9×10^{-12}	1.4
$\xrightarrow{M} H_2O_2$	(See Table 2)			
$OH + H_2O_2 \rightarrow H_2O + HO_2$	2.9×10^{-12}	160±100	1.7×10^{-12}	1.2
$OH + H_2 \rightarrow H_2O + H$	5.5×10^{-12}	2000±400	6.7×10^{-15}	1.2
$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$	2.3×10^{-13}	-(600±200)	1.7×10^{-12}	1.3
$\xrightarrow{M} H_2O_2 + O_2$	1.7×10^{-33}[M]	-(1000±400)	4.9×10^{-32}[M]	1.3
$HO_2 + O_3 \rightarrow OH + 2O_2$	1.1×10^{-14}	500^{+500}_{-100}	2.0×10^{-15}	1.3
		NO_x Reactions		
$N + O_2 \rightarrow NO + O$	1.5×10^{-11}	3600±400	8.5×10^{-17}	1.25
$N + O_3 \rightarrow NO + O_2$	-	-	$<2.0\times10^{-16}$	-
$N + NO \rightarrow N_2 + O$	3.4×10^{-11}	0±100	3.4×10^{-11}	1.3
$N + NO_2 \rightarrow N_2O + O$	-	-	3.0×10^{-12}	3.0
$O + NO \xrightarrow{M} NO_2$	(See Table 2)			
$O + NO_2 \rightarrow NO + O_2$	6.5×10^{-12}	-(120±120)	9.7×10^{-12}	1.1
$O + NO_2 \xrightarrow{M} NO_3$	(See Table 2)			
$O + NO_3 \rightarrow O_2 + NO_2$	1.0×10^{-11}	0±150	1.0×10^{-11}	1.5
$O + N_2O_5 \rightarrow$ products	-	-	$<3.0\times10^{-16}$	-
$O + HNO_3 \rightarrow OH + NO_3$	-	-	$<3.0\times10^{-17}$	-
$O + HO_2NO_2 \rightarrow$ products	7.8×10^{-11}	3400±750	8.6×10^{-16}	3.0

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$O_3 + NO \rightarrow NO_2 + O_2$	$2.0x10^{-12}$	1400±200	$1.8x10^{-14}$	1.2
$NO + HO_2 \rightarrow NO_2 + OH$	$3.7x10^{-12}$	-(240±80)	$8.3x10^{-12}$	1.2
$NO + NO_3 \rightarrow 2NO_2$	$1.7x10^{-11}$	-(150±100)	$2.9x10^{-11}$	1.3
$OH + NO \xrightarrow{M} HONO$	(See Table 2)			
$OH + NO_2 \xrightarrow{M} HNO_3$	(See Table 2)			
$OH + NO_3 \rightarrow$ products	-	-	$2.3x10^{-11}$	2.0
$OH + HNO_3 \rightarrow H_2O + NO_3$	(See ≠ below)		1.3	
$OH + HO_2NO_2 \rightarrow$ products	$1.3x10^{-12}$	$-(380\pm^{270}_{500})$	$4.6x10^{-12}$	1.5
$HO_2 + NO_2 \xrightarrow{M} HO_2NO_2$	(See Table 2)			
$HO_2 + NO_3 \rightarrow$ products	-	-	$4.1x10^{-12}$	2.0
$O_3 + NO_2 \rightarrow NO_3 + O_2$	$1.2x10^{-13}$	2450±150	$3.2x10^{-17}$	1.15
$O_3 + HNO_2 \rightarrow O_2 + HNO_3$	-	-	$<5.0x10^{-19}$	-
$NO_2 + NO_3 \xrightarrow{M} N_2O_5$	(See Table 2)			
$NO_2 + NO_3 \rightarrow NO + NO_2 + O_2$				
$N_2O_5 + H_2O \rightarrow 2HNO_3$	-	-	$<2.0x10^{-21}$	-
$OH + NH_3 \rightarrow H_2O + NH_2$	$3.6x10^{-12}$	930±200	$1.6x10^{-13}$	1.4
$NH_2 + HO_2 \rightarrow$ products	-	-	$3.4x10^{-11}$	2.0
$NH_2 + NO \rightarrow$ products	$3.8x10^{-12}$	-(450±150)	$1.7x10^{-11}$	2.0
$NH_2 + NO_2 \rightarrow$ products	$2.1x10^{-12}$	-(650±250)	$1.9x10^{-11}$	3.0
$NH_2 + O_2 \rightarrow$ products	-	-	$<3.0x10^{-18}$	-
$NH_2 + O_3 \rightarrow$ products	$4.3x10^{-12}$	930±500	$1.9x10^{-13}$	3.0

≠ $OH + HNO_3$ pressure and temperature dependence fit by

$$k(M,T) = k_o + \frac{k_3[M]}{1 + \frac{k_3[M]}{k_2}} \quad \text{with} \quad \begin{aligned} k_o &= 7.2 \times 10^{-15} \exp(785/T) \\ k_2 &= 4.1 \times 10^{-16} \exp(1440/T) \\ k_3 &= 1.9 \times 10^{-33} \exp(725/T) \end{aligned}$$

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
		Hydrocarbon Reactions		
$OH + CO \rightarrow CO_2 + H$	$1.5\times10^{-13}(1+0.6P_{atm})$	0±300	$1.5\times10^{-13}(1+0.6P_{atm})$	1.3
$OH + CH_4 \rightarrow CH_3 + H_2O$	2.3×10^{-12}	1700±200	7.7×10^{-15}	1.2
$OH + {}^{13}CH_4 \rightarrow {}^{13}CH_3 + H_2O$				
$OH + C_2H_6 \rightarrow H_2O + C_2H_5$	1.1×10^{-11}	1100±200	2.8×10^{-13}	1.2
$OH + C_3H_8 \rightarrow H_2O + C_3H_7$	1.4×10^{-11}	750±200	1.1×10^{-12}	1.3
$OH + C_2H_4 \rightarrow$ products	(See Table 2)			
$OH + C_2H_2 \rightarrow$ products	(See Table 2)			
$OH + H_2CO \rightarrow H_2O + HCO$	1.0×10^{-11}	0±200	1.0×10^{-11}	1.25
$OH + CH_3OH \rightarrow$ products	6.7×10^{-12}	600±300	8.9×10^{-13}	1.2
$OH + C_2H_5OH \rightarrow$ products	6.8×10^{-12}	225±100	3.2×10^{-12}	1.3
$OH + CH_3CHO \rightarrow CH_3CO + H_2O$	6.0×10^{-12}	-(250±200)	1.4×10^{-11}	1.4
$OH + CH_3OOH \rightarrow$ products	3.8×10^{-12}	-(200±200)	7.4×10^{-12}	1.5
$OH + HCN \rightarrow$ products	1.2×10^{-13}	400±150	3.1×10^{-14}	3.0
$OH + CH_3CN \rightarrow$ products	4.5×10^{-13}	900±400	2.2×10^{-14}	2.0
$O_3 + C_2H_2 \rightarrow$ products	1.0×10^{-14}	4100±500	1.0×10^{-20}	3.0
$O_3 + C_2H_4 \rightarrow$ products	1.2×10^{-14}	2630±100	1.7×10^{-18}	1.25
$O_3 + C_3H_6 \rightarrow$ products	6.5×10^{-15}	1900±200	1.1×10^{-17}	1.2
$HO_2 + CH_2O \rightarrow$ adduct	6.7×10^{-15}	-(600±600)	5.0×10^{-14}	5.0
$O + HCN \rightarrow$ products	1.0×10^{-11}	4000±1000	1.5×10^{-17}	10.0
$O + C_2H_2 \rightarrow$ products	3.0×10^{-11}	1600±250	1.4×10^{-13}	1.3
$O + H_2CO \rightarrow$ products	3.4×10^{-11}	1600±250	1.6×10^{-13}	1.25
$O + CH_3CHO \rightarrow CH_3CO + OH$	1.8×10^{-11}	1100±200	4.5×10^{-13}	1.25
$O + CH_3 \rightarrow$ products	1.1×10^{-10}	0±250	1.1×10^{-10}	1.3
$CH_3 + O_2 \rightarrow$ products	-	-	$<3.0\times10^{-16}$	-

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$CH_3 + O_2 \xrightarrow{M} CH_3O_2$	(See Table 2)			
$C_2H_5 + O_2 \rightarrow C_2H_4 + HO_2$	-	-	$<2.0\times10^{-15}$	-
$C_2H_5 + O_2 \xrightarrow{M} C_2H_5O_2$	(See Table 2)			
$CH_2OH + O_2 \rightarrow CH_2O + HO_2$	(See Note)		9.1×10^{-12}	1.3
$CH_3O + O_2 \rightarrow CH_2O + HO_2$	3.9×10^{-14}	900±300	1.9×10^{-15}	1.5
$HCO + O_2 \rightarrow CO + HO_2$	3.5×10^{-12}	-(140±140)	5.5×10^{-12}	1.3
$CH_3 + O_3 \rightarrow$ products	5.4×10^{-12}	220±150	2.6×10^{-12}	2.0
$CH_3O_2 + O_3 \rightarrow$ products	-	-	$<3.0\times10^{-17}$	-
$CH_3O_2 + CH_3O_2 \rightarrow$ products	2.2×10^{-13}	-(220±220)	4.6×10^{-13}	1.5
$CH_3O_2 + NO \rightarrow CH_3O + NO_2$	4.2×10^{-12}	-(180±180)	7.6×10^{-12}	1.2
$CH_3O_2 + NO_2 \xrightarrow{M} CH_3O_2NO_2$	(See Table 2)			
$CH_3O_2 + HO_2 \rightarrow$ products	3.3×10^{-13}	-(800±400)	4.8×10^{-12}	2.0
$C_2H_5O_2 + C_2H_5O_2 \rightarrow$ products	1.6×10^{-13}	300±250	5.8×10^{-14}	2.0
$C_2H_5O_2 + NO \rightarrow$ products	8.9×10^{-12}	0±300	8.9×10^{-12}	1.3
$C_2H_5O_2 + HO_2 \rightarrow$ products	6.5×10^{-13}	-(650±300)	5.6×10^{-12}	2.0
$NO_3 + CO \rightarrow$ products	-	-	$<4.0\times10^{-19}$	-
$NO_3 + CH_2O \rightarrow$ products	-	-	5.8×10^{-16}	1.3
$NO_3 + CH_3CHO \rightarrow$ products	1.4×10^{-12}	1900±300	2.4×10^{-15}	1.3
		ClO_x Reactions		
$Cl + O_3 \rightarrow ClO + O_2$	2.8×10^{-11}	250±100	1.2×10^{-11}	1.15
$Cl + H_2 \rightarrow HCl + H$	3.7×10^{-11}	2300±200	1.6×10^{-14}	1.25
$Cl + CH_4 \rightarrow HCl + CH_3$	1.1×10^{-11}	1400±150	1.0×10^{-13}	1.1
$Cl + C_2H_6 \rightarrow HCl + C_2H_5$	7.7×10^{-11}	90±90	5.7×10^{-11}	1.1
$Cl + C_3H_8 \rightarrow HCl + C_3H_7$	1.4×10^{-10}	-(40±250)	1.6×10^{-10}	1.5

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$Cl + C_2H_2 \rightarrow products$	(See Table 2)			
$Cl + CH_3OH \rightarrow CH_2OH + HCl$	5.7×10^{-11}	0±250	5.7×10^{-11}	1.5
$Cl + CH_3Cl \rightarrow CH_2Cl + HCl$	3.3×10^{-11}	1250±200	4.9×10^{-13}	1.2
$Cl + CH_3CN \rightarrow products$	-	-	$<2.0\times10^{-15}$	-
$Cl + CH_3CCl_3 \rightarrow CH_2CCl_3 + HCl$	-	-	$<4.0\times10^{-14}$	-
$Cl + H_2CO \rightarrow HCl + HCO$	8.1×10^{-11}	30±100	7.3×10^{-11}	1.15
$Cl + H_2O_2 \rightarrow HCl + HO_2$	1.1×10^{-11}	980±500	4.1×10^{-13}	1.5
$Cl + HOCl \rightarrow Cl_2 + OH$	3.0×10^{-12}	130±250	1.9×10^{-12}	2.0
$Cl + HNO_3 \rightarrow products$	-	-	$<2.0\times10^{-16}$	-
$Cl + HO_2 \rightarrow HCl + O_2$	1.8×10^{-11}	-(170±200)	3.2×10^{-11}	1.5
$\rightarrow OH + ClO$	4.1×10^{-11}	450±200	9.1×10^{-12}	2.0
$Cl + Cl_2O \rightarrow Cl_2 + ClO$	9.8×10^{-11}	0±250	9.8×10^{-11}	1.2
$Cl + OClO \rightarrow ClO + ClO$	3.4×10^{-11}	-(160±200)	5.8×10^{-11}	1.25
$Cl + ClOO \rightarrow Cl_2 + O_2$	1.4×10^{-10}	0±250	1.4×10^{-10}	3.0
$\rightarrow ClO + ClO$	8.0×10^{-12}	0±250	8.0×10^{-12}	3.0
$Cl + Cl_2O_2 \rightarrow products$	-	-	1.0×10^{-10}	2.0
$Cl + ClONO_2 \rightarrow products$	6.8×10^{-12}	-(160±200)	1.2×10^{-11}	1.3
$Cl + NO \xrightarrow{M} NOCl$	(See Table 2)			
$Cl + NO_2 \xrightarrow{M} ClONO\ (ClNO_2)$	(See Table 2)			
$Cl + NO_3 \rightarrow ClO + NO_2$	2.6×10^{-11}	0±400	2.6×10^{-11}	2.0
$Cl + N_2O \rightarrow ClO + N_2$				
$Cl + ClNO \rightarrow NO + Cl_2$	5.8×10^{-11}	-(100±200)	8.1×10^{-11}	1.5
$Cl + O_2 \xrightarrow{M} ClOO$	(See Table 2)			
$ClO + O \rightarrow Cl + O_2$	3.0×10^{-11}	-(70±70)	3.8×10^{-11}	1.2
$ClO + NO \rightarrow NO_2 + Cl$	6.4×10^{-12}	-(290±100)	1.7×10^{-11}	1.15

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$ClO + NO_2 \xrightarrow{M} ClONO_2$	(See Table 2)			
$ClO + NO_3 \rightarrow$ products	4.0×10^{-13}	0±400	4.0×10^{-13}	2.0
$ClO + HO_2 \rightarrow HOCl + O_2$	4.6×10^{-13}	$-(700\pm^{250}_{700})$	5.0×10^{-12}	1.4
$ClO + H_2CO \rightarrow$ products	$\sim1.0\times10^{-12}$	>2100	$<1.0\times10^{-15}$	-
$ClO + OH \rightarrow$ products	1.1×10^{-11}	-(120±150)	1.7×10^{-11}	1.5
$ClO + CH_4 \rightarrow$ products	$\sim1.0\times10^{-12}$	>3700	$<4.0\times10^{-18}$	-
$ClO + H_2 \rightarrow$ products	$\sim1.0\times10^{-12}$	>4800	$<1.0\times10^{-19}$	-
$ClO + CO \rightarrow$ products	$\sim1.0\times10^{-12}$	>3700	$<4.0\times10^{-18}$	-
$ClO + N_2O \rightarrow$ products	$\sim1.0\times10^{-12}$	>4300	$<6.0\times10^{-19}$	-
$ClO + ClO \rightarrow$ products	8.0×10^{-13}	1250±500	1.2×10^{-14}	2.0
$\xrightarrow{M} Cl_2O_2$	(See Table 2)			
$ClO + O_3 \rightarrow ClOO + O_2$	1.0×10^{-12}	>4000	$<1.0\times10^{-18}$	-
$\rightarrow OClO + O_2$	1.0×10^{-12}	>4000	$<1.0\times10^{-18}$	-
$ClO + CH_3O_2 \rightarrow$ products	(See Note)			
$OH + Cl_2 \rightarrow HOCl + Cl$	1.4×10^{-12}	900±400	6.7×10^{-14}	1.2
$OH + HCl \rightarrow H_2O + Cl$	2.6×10^{-12}	350±100	8.0×10^{-13}	1.3
$OH + HOCl \rightarrow H_2O + ClO$	3.0×10^{-12}	500±500	5.0×10^{-13}	3.0
$OH + CH_3Cl \rightarrow CH_2Cl + H_2O$	2.1×10^{-12}	1150±200	4.4×10^{-14}	1.2
$OH + CH_2Cl_2 \rightarrow CHCl_2 + H_2O$	5.8×10^{-12}	1100±250	1.4×10^{-13}	1.2
$OH + CHCl_3 \rightarrow CCl_3 + H_2O$	4.3×10^{-12}	1100±200	1.1×10^{-13}	1.2
$OH + CHFCl_2 \rightarrow CFCl_2 + H_2O$	1.2×10^{-12}	1100±150	3.0×10^{-14}	1.1
$OH + CHF_2Cl \rightarrow CF_2Cl + H_2O$	1.2×10^{-12}	1650±150	4.7×10^{-15}	1.1
$OH + CH_2ClF \rightarrow CHClF + H_2O$	3.0×10^{-12}	1250±200	4.5×10^{-14}	1.15
$OH + CH_3CCl_3 \rightarrow CH_2CCl_3 + H_2O$	5.0×10^{-12}	1800±200	1.2×10^{-14}	1.3
$OH + CHCl_2CF_3 \rightarrow CCl_2CF_3 + H_2O$	6.4×10^{-13}	850±250	3.7×10^{-14}	1.2

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$OH + CHFClCF_3 \rightarrow CFClCF_3 + H_2O$	6.6×10^{-13}	1250±300	1.0×10^{-14}	1.2
$OH + CH_2ClCF_2Cl \rightarrow CHClCF_2Cl + H_2O$	3.6×10^{-12}	1600±400	1.7×10^{-14}	2.0
$OH + CH_2ClCF_3 \rightarrow CHClCF_3 + H_2O$	5.2×10^{-13}	1100±300	1.3×10^{-14}	1.3
$OH + CH_3CFCl_2 \rightarrow CH_2CFCl_2 + H_2O$	4.2×10^{-13}	1200±300	7.5×10^{-15}	1.3
$OH + CH_3CF_2Cl \rightarrow CH_2CF_2Cl + H_2O$	9.6×10^{-13}	1650±250	3.8×10^{-15}	1.2
$OH + C_2Cl_4 \rightarrow$ products	9.4×10^{-12}	1200±200	1.7×10^{-13}	1.25
$OH + C_2HCl_3 \rightarrow$ products	4.9×10^{-13}	-(450±200)	2.2×10^{-12}	1.25
$OH + CCl_4 \rightarrow$ products	$\sim 1.0 \times 10^{-12}$	>2300	$< 5.0 \times 10^{-16}$	-
$OH + CFCl_3 \rightarrow$ products	$\sim 1.0 \times 10^{-12}$	>3700	$< 5.0 \times 10^{-18}$	-
$OH + CF_2Cl_2 \rightarrow$ products	$\sim 1.0 \times 10^{-12}$	>3600	$< 6.0 \times 10^{-18}$	-
$OH + ClONO_2 \rightarrow$ products	1.2×10^{-12}	330±200	3.9×10^{-13}	1.5
$O + HCl \rightarrow OH + Cl$	1.0×10^{-11}	3300±350	1.5×10^{-16}	2.0
$O + HOCl \rightarrow OH + ClO$	1.0×10^{-11}	2200±1000	6.0×10^{-15}	10.0
$O + ClONO_2 \rightarrow$ products	2.9×10^{-12}	800±200	2.0×10^{-13}	1.5
$O + Cl_2O \rightarrow ClO + ClO$	2.9×10^{-11}	630±200	3.5×10^{-12}	1.4
$OClO + O \rightarrow ClO + O_2$	2.8×10^{-11}	1200±300	5.0×10^{-13}	2.0
$OClO + O_3 \rightarrow$ products	2.1×10^{-12}	4700±1000	3.0×10^{-19}	2.5
$OClO + OH \rightarrow HOCl + O_2$	4.5×10^{-13}	-(800±200)	6.8×10^{-12}	2.0
$OClO + NO \rightarrow NO_2 + ClO$	2.5×10^{-12}	600±300	3.4×10^{-13}	2.0
$Cl_2O_2 + O_3 \rightarrow$ products	-	-	$< 1.0 \times 10^{-19}$	-
$Cl_2O_2 + NO \rightarrow$ products	-	-	$< 2.0 \times 10^{-14}$	-
$HCl + NO_3 \rightarrow HNO_3 + Cl$	-	-	$< 5.0 \times 10^{-17}$	-
$HCl + ClONO_2 \rightarrow$ products	-	-	$< 1.0 \times 10^{-20}$	-
$HCl + HO_2NO_2 \rightarrow$ products	-	-	$< 1.0 \times 10^{-21}$	-
$H_2O + ClONO_2 \rightarrow$ products	-	-	$< 2.0 \times 10^{-21}$	-

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$CF_2ClO_2 + NO \rightarrow CF_2ClO + NO_2$	3.1×10^{-12}	-(500±200)	1.6×10^{-11}	1.3
$CFCl_2O_2 + NO \rightarrow CFCl_2O + NO_2$	3.5×10^{-12}	-(430±200)	1.5×10^{-11}	1.3
$CCl_3O_2 + NO \rightarrow CCl_3O + NO_2$	5.7×10^{-12}	-(330±200)	1.7×10^{-11}	1.3
		BrO_x Reactions		
$Br + O_3 \rightarrow BrO + O_2$	1.7×10^{-11}	800±200	1.2×10^{-12}	1.2
$Br + H_2O_2 \rightarrow HBr + HO_2$	1.0×10^{-11}	>3000	$<5.0\times10^{-16}$	-
$Br + H_2CO \rightarrow HBr + HCO$	1.7×10^{-11}	800±200	1.1×10^{-12}	1.3
$Br + HO_2 \rightarrow HBr + O_2$	1.5×10^{-11}	600±600	2.0×10^{-12}	2.0
$Br + Cl_2O \rightarrow BrCl + ClO$	2.0×10^{-11}	500±300	3.8×10^{-12}	2.0
$Br + OClO \rightarrow BrO + ClO$	2.6×10^{-11}	1300±300	3.4×10^{-13}	2.0
$Br + Cl_2O_2 \rightarrow$ products	-	-	3.0×10^{-12}	2.0
$BrO + O \rightarrow Br + O_2$	3.0×10^{-11}	0±250	3.0×10^{-11}	3.0
$BrO + ClO \rightarrow Br + OClO$	1.6×10^{-12}	-(430±200)	6.8×10^{-12}	1.25
$\rightarrow Br + ClOO$	2.9×10^{-12}	-(220±200)	6.1×10^{-12}	1.25
$\rightarrow BrCl + O_2$	5.8×10^{-13}	-(170±200)	1.0×10^{-12}	1.25
$BrO + NO \rightarrow NO_2 + Br$	8.8×10^{-12}	-(260±130)	2.1×10^{-11}	1.15
$BrO + NO_2 \xrightarrow{M} BrONO_2$	(See Table 2)			
$BrO + BrO \rightarrow 2\ Br + O_2$	1.4×10^{-12}	-(150±150)	2.3×10^{-12}	1.25
$\rightarrow Br_2 + O_2$	6.0×10^{-14}	-(600±600)	4.4×10^{-13}	1.25
$BrO + O_3 \rightarrow Br + 2O_2$	$\sim1.0\times10^{-12}$	>1600	$<5.0\times10^{-15}$	-
$BrO + HO_2 \rightarrow$ products	-	-	5.0×10^{-12}	3.0
$BrO + OH \rightarrow$ products	-	-	1.0×10^{-11}	5.0
$OH + Br_2 \rightarrow HOBr + Br$	4.2×10^{-11}	0±600	4.2×10^{-11}	1.3
$OH + HBr \rightarrow H_2O + Br$	1.1×10^{-11}	0±250	1.1×10^{-11}	1.2

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$OH + CH_3Br \rightarrow CH_2Br + H_2O$	6.8×10^{-13}	850±200	3.8×10^{-14}	1.25
$OH + CF_2Br_2 \rightarrow$ products	-	-	$<5.0 \times 10^{-16}$	-
$OH + CF_2ClBr \rightarrow$ products	-	-	$<1.5 \times 10^{-16}$	-
$OH + CF_3Br \rightarrow$ products	-	-	$<1.2 \times 10^{-16}$	-
$OH + CF_2BrCF_2Br \rightarrow$ products	-	-	$<1.5 \times 10^{-16}$	-
$O + HBr \rightarrow OH + Br$	5.8×10^{-12}	1500±200	3.8×10^{-14}	1.3
$NO_3 + Br \rightarrow BrO + NO_2$	-	-	1.6×10^{-11}	2.0
$NO_3 + BrO \rightarrow$ products	-	-	1.0×10^{-12}	3.0
$NO_3 + HBr \rightarrow HNO_3 + Br$	-	-	$<1.0 \times 10^{-16}$	-
		FO_x Reactions		
$F + O_3 \rightarrow FO + O_2$	2.8×10^{-11}	230±200	1.3×10^{-11}	2.0
$F + H_2 \rightarrow HF + H$	1.4×10^{-10}	500±200	2.6×10^{-11}	1.2
$F + CH_4 \rightarrow HF + CH_3$	3.0×10^{-10}	400±300	8.0×10^{-11}	1.5
$F + H_2O \rightarrow HF + OH$	1.4×10^{-11}	0±200	1.4×10^{-11}	1.3
$F + O_2 \xrightarrow{M} FO_2$	(See Table 2)			
$F + NO \xrightarrow{M} FNO$	(See Table 2)			
$F + NO_2 \xrightarrow{M} FNO_2(FONO)$	(See Table 2)			
$F + HNO_3 \rightarrow HF + NO_3$	6.0×10^{-12}	-(400±200)	2.3×10^{-11}	1.3
$NO + FO \rightarrow NO_2 + F$	2.6×10^{-11}	0±250	2.6×10^{-11}	2.0
$FO + FO \rightarrow 2\ F + O_2$	1.5×10^{-11}	0±250	1.5×10^{-11}	3.0
$FO + O_3 \rightarrow F + 2\ O_2$				
$\rightarrow FO_2 + O_2$				
$FO + NO_2 \xrightarrow{M} FONO_2$	(See Table 2)			
$O + FO \rightarrow F + O_2$	5.0×10^{-11}	0±250	5.0×10^{-11}	3.0

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$O + FO_2 \rightarrow FO + O_2$	5.0×10^{-11}	0±250	5.0×10^{-11}	5.0
$OH + CHF_3 \rightarrow CF_3 + H_2O$	1.5×10^{-12}	2650±500	2.1×10^{-16}	1.5
$OH + CH_2F_2 \rightarrow CHF_2 + H_2O$	2.5×10^{-12}	1650±200	1.0×10^{-14}	1.2
$OH + CH_3F \rightarrow CH_2F + H_2O$	5.4×10^{-12}	1700±300	1.8×10^{-14}	1.2
$OH + CHF_2CF_3 \rightarrow CF_2CF_3 + H_2O$	8.9×10^{-13}	1750±500	2.5×10^{-15}	2.0
$OH + CHF_2CHF_2 \rightarrow CF_2CHF_2 + H_2O$	8.7×10^{-13}	1500±500	5.7×10^{-15}	2.0
$OH + CH_2FCF_3 \rightarrow CHFCF_3 + H_2O$	1.7×10^{-12}	1750±300	4.8×10^{-15}	1.2
$OH + CH_2FCHF_2 \rightarrow$ products	2.8×10^{-12}	1500±500	1.8×10^{-14}	2.0
$OH + CH_3CF_3 \rightarrow CH_2CF_3 + H_2O$	6.0×10^{-13}	1750±500	1.7×10^{-15}	2.0
$OH + CH_2FCH_2F \rightarrow CHFCH_2F + H_2O$	1.7×10^{-11}	1500±500	1.1×10^{-13}	2.0
$OH + CH_3CHF_2 \rightarrow$ products	1.5×10^{-12}	1100±200	3.7×10^{-14}	1.1
$OH + CH_3CH_2F \rightarrow$ products	1.3×10^{-11}	1200±300	2.3×10^{-13}	2.0
$CF_3O_2 + NO \rightarrow CF_3O + NO_2$	3.9×10^{-12}	-(400±200)	1.5×10^{-11}	1.3
		SO_x Reactions		
$OH + H_2S \rightarrow SH + H_2O$	6.0×10^{-12}	75±75	4.7×10^{-12}	1.2
$OH + OCS \rightarrow$ products	1.1×10^{-13}	1200±500	1.9×10^{-15}	2.0
$OH + CS_2 \rightarrow$ products	(See Note)	-	-	-
$OH + SO_2 \xrightarrow{M} HOSO_2$	(See Table 2)			
$O + H_2S \rightarrow OH + SH$	9.2×10^{-12}	1800±550	2.2×10^{-14}	1.7
$O + OCS \rightarrow CO + SO$	2.1×10^{-11}	2200±150	1.3×10^{-14}	1.2
$O + CS_2 \rightarrow CS + SO$	3.2×10^{-11}	650±150	3.6×10^{-12}	1.2
$S + O_2 \rightarrow SO + O$	2.3×10^{-12}	0±200	2.3×10^{-12}	1.2
$S + O_3 \rightarrow SO + O_2$	-	-	1.2×10^{-11}	2.0
$S + OH \rightarrow SO + H$	-	-	6.6×10^{-11}	3.0

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$SO + O_2 \rightarrow SO_2 + O$	2.6×10^{-13}	2400±500	8.4×10^{-17}	2.0
$SO + O_3 \rightarrow SO_2 + O_2$	3.6×10^{-12}	1100±200	9.0×10^{-14}	1.2
$SO + OH \rightarrow SO_2 + H$	-	-	8.6×10^{-11}	2.0
$SO + NO_2 \rightarrow SO_2 + NO$	1.4×10^{-11}	0±50	1.4×10^{-11}	1.2
$SO + ClO \rightarrow SO_2 + Cl$	2.8×10^{-11}	0±50	2.8×10^{-11}	1.3
$SO + OClO \rightarrow SO_2 + ClO$	-	-	1.9×10^{-12}	3.0
$SO + BrO \rightarrow SO_2 + Br$	-	-	5.7×10^{-11}	1.4
$SO_2 + HO_2 \rightarrow$ products	-	-	$<1.0 \times 10^{-18}$	-
$SO_2 + CH_3O_2 \rightarrow$ products	-	-	$<5.0 \times 10^{-17}$	-
$SO_2 + NO_2 \rightarrow$ products	-	-	$<2.0 \times 10^{-26}$	-
$SO_3 + NO_2 \rightarrow$ products	-	-	1.0×10^{-19}	10.0
$SO_2 + NO_3 \rightarrow$ products	-	-	$<7.0 \times 10^{-21}$	-
$SO_2 + O_3 \rightarrow SO_3 + O_2$	3.0×10^{-12}	>7000	$<2.0 \times 10^{-22}$	-
$SO_3 + H_2O \rightarrow H_2SO_4$	-	-	$<6.0 \times 10^{-15}$	-
$Cl + H_2S \rightarrow HCl + SH$	5.7×10^{-11}	0±50	5.7×10^{-11}	1.3
$Cl + OCS \rightarrow SCl + CO$	-	-	$<1.0 \times 10^{-16}$	-
$ClO + OCS \rightarrow$ products	-	-	$<2.0 \times 10^{-16}$	-
$ClO + SO_2 \rightarrow Cl + SO_3$	-	-	$<4.0 \times 10^{-18}$	-
$SH + H_2O_2 \rightarrow$ products	-	-	$<5.0 \times 10^{-15}$	-
$SH + O \rightarrow H + SO$	-	-	1.6×10^{-10}	5.0
$SH + O_2 \rightarrow OH + SO$	-	-	$<4.0 \times 10^{-19}$	-
$SH + O_3 \rightarrow HSO + O_2$	9.0×10^{-12}	280±200	3.5×10^{-12}	1.3
$SH + NO_2 \rightarrow HSO + NO$	2.9×10^{-11}	-(240±100)	6.5×10^{-11}	1.3
$SH + NO \xrightarrow{M} HSNO$	(See Table 2)			
$HSO + NO \rightarrow$ products	-	-	$<1.0 \times 10^{-15}$	-

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
$HSO + NO_2 \rightarrow HSO_2 + NO$	-	-	9.6×10^{-12}	2.0
$HSO + O_2 \rightarrow$ products	-	-	$<2.0\times10^{-17}$	-
$HSO + O_3 \rightarrow$ products	-	-	1.0×10^{-13}	5.0
$HSO_2 + O_2 \rightarrow HO_2 + SO_2$	-	-	3.0×10^{-13}	3.0
$HOSO_2 + O_2 \rightarrow HO_2 + SO_3$	1.3×10^{-12}	330±200	4.4×10^{-13}	1.2
$H_2S + NO_3 \rightarrow$ products	-	-	$<8.0\times10^{-16}$	-
$CS + O_2 \rightarrow OCS + O$	-	-	2.9×10^{-19}	2.0
$CS + O_3 \rightarrow OCS + O_2$	-	-	3.0×10^{-16}	3.0
$CS + NO_2 \rightarrow OCS + NO$	-	-	7.6×10^{-17}	3.0
$OH + CH_3SH \rightarrow$ products	9.9×10^{-12}	-(360±100)	3.3×10^{-11}	1.2
$OH + CH_3SCH_3 \rightarrow H_2O + CH_2SCH_3$	1.1×10^{-11}	240±100	4.9×10^{-12}	1.2
$OH + CH_3SSCH_3 \rightarrow$ products	5.7×10^{-11}	-(380±300)	2.0×10^{-10}	1.3
$NO_3 + CH_3SH \rightarrow$ products	4.4×10^{-13}	-(210±210)	8.9×10^{-13}	1.25
$NO_3 + CH_3SCH_3 \rightarrow$ products	1.9×10^{-13}	-(500±200)	1.0×10^{-12}	1.2
$NO_3 + CH_3SSCH_3 \rightarrow$ products	1.3×10^{-12}	270±270	5.3×10^{-13}	1.4
$NO_3 + CS_2 \rightarrow$ products	-	-	$<4.0\times10^{-16}$	-
$NO_3 + OCS \rightarrow$ products	-	-	$<3.0\times10^{-15}$	-
$CH_3S + O_2 \rightarrow$ products	-	-	$<3.0\times10^{-18}$	-
$CH_3S + O_3 \rightarrow$ products	-	-	4.1×10^{-12}	2.0
$CH_3S + NO_2 \rightarrow$ products	-	-	5.6×10^{-11}	1.3
$CH_3SO + O_3 \rightarrow$ products	-	-	1.0×10^{-12}	3.0
$CH_3SO + NO_2 \rightarrow CH_3SO_2 + NO$	-	-	1.2×10^{-11}	1.4

Table 1. (Continued)

Reaction	A-Factor[a]	E/R±(ΔE/R)	k(298 K)	f(298)[b]
		Metal Reactions		
$Na + O_2 \xrightarrow{M} NaO_2$	(See Table 2)			
$Na + O_3 \rightarrow NaO + O_2$	7.6×10^{-10}	0±400	7.6×10^{-10}	1.2
$\rightarrow NaO_2 + O$	$<4\times10^{-11}$	0±400	$<4.0\times10^{-11}$	-
$Na + N_2O \rightarrow NaO + N_2$	2.4×10^{-10}	1600±400	1.1×10^{-12}	1.3
$Na + Cl_2 \rightarrow NaCl + Cl$	7.3×10^{-10}	0±200	7.3×10^{-10}	1.3
$NaO + O \rightarrow Na + O_2$	3.7×10^{-10}	0±400	3.7×10^{-10}	3.0
$NaO + O_2 \xrightarrow{M} NaO_3$	(See Table 2)			
$NaO + O_3 \rightarrow NaO_2 + O_2$	1.6×10^{-10}	0±400	1.6×10^{-10}	2.0
$\rightarrow Na + 2O_2$	6×10^{-11}	0±800	6.0×10^{-11}	3.0
$NaO + H_2 \rightarrow NaOH + H$	2.6×10^{-11}	0±600	2.6×10^{-11}	2.0
$NaO + H_2O \rightarrow NaOH + OH$	2.2×10^{-10}	0±400	2.2×10^{-10}	2.0
$NaO + NO \rightarrow Na + NO_2$	1.5×10^{-10}	0±400	1.5×10^{-10}	4.0
$NaO + CO_2 \xrightarrow{M} NaCO_3$	(See Table 2)			
$NaO + HCl \rightarrow$ products	2.8×10^{-10}	0±400	2.8×10^{-10}	3.0
$NaO_2 + NO \rightarrow NaO + NO_2$			$<10^{-14}$	
$NaO_2 + HCl \rightarrow$ products	2.3×10^{-10}	0±400	2.3×10^{-10}	3.0
$NaOH + HCl \rightarrow NaCl + H_2O$	2.8×10^{-10}	0±400	2.8×10^{-10}	3.0
$NaOH + CO_2 \xrightarrow{M} NaHCO_3$	(See Table 2)			

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[a] Units are cm^3 molecules-^{1}sec-^{1}.

[b] f(298) is the uncertainty factor at 298K. To calculate the uncertainty at other temperatures, use the expression: $f(T) = f(298) \exp \left| \frac{\Delta E}{R} \left(\frac{1}{T} - \frac{1}{298}\right) \right|$. Note that the exponent is absolute value.

Table 2. Rate Constants for Three-Body Reactions

	Low Pressure Limit[a] $k_o(T) = k_o^{300}(T/300)^{-n}$		High Pressure Limit[b] $k_\infty(T) = k_\infty^{300}(T/300)^{-m}$	
Reaction	k_o^{300}	n	k_∞^{300}	m
$O + O_2 \xrightarrow{M} O_3$	(6.0±0.5)(-34)	2.3±0.5	- -	-
$O(^1D) + N_2 \xrightarrow{M} N_2O$	(3.5±3.0)(-37)	$0.6\pm^{2.0}_{0.6}$	- -	-
$H + O_2 \xrightarrow{M} HO_2$	(5.7±0.5)(-32)	1.6±0.5	(7.5±4.0)(-11)	0±1
$OH + OH \xrightarrow{M} H_2O_2$	(6.9±3.0)(-31)	$0.8\pm^{2.0}_{0.8}$	(1.5±0.5)(-11)	0±0.5
$O + NO \xrightarrow{M} NO_2$	(9.0±2.0)(-32)	1.5±0.3	(3.0±1.0)(-11)	0±1
$O + NO_2 \xrightarrow{M} NO_3$	(9.0±1.0)(-32)	2.0±1.0	(2.2±0.3)(-11)	0±1
$OH + NO \xrightarrow{M} HONO$	(7.0±2.0)(-31)	2.6±1.0	(1.5±1.0)(-11)	0.5±0.5
$OH + NO_2 \xrightarrow{M} HNO_3$	(2.6±0.3)(-30)	3.2±0.7	(2.4±1.2)(-11)	1.3±1.3
$HO_2 + NO_2 \xrightarrow{M} HO_2NO_2$	(1.8±0.3)(-31)	3.2±0.4	(4.7±1.0)(-12)	1.4±1.4
$NO_2 + NO_3 \xrightarrow{M} N_2O_5$	(2.2±0.5)(-30)	4.3±1.3	(1.5±0.8)(-12)	0.5±0.5
$Cl + NO \xrightarrow{M} ClNO$	(9.0±2.0)(-32)	1.6±0.5	- -	-
$Cl + NO_2 \xrightarrow{M} ClONO$	(1.3±0.2)(-30)	2.0±1.0	(1.0±0.5)(-10)	1±1
$\xrightarrow{M} ClNO_2$	(1.8±0.3)(-31)	2.0±1.0	(1.0±0.5)(-10)	1±1
$Cl + O_2 \xrightarrow{M} ClOO$	(2.7±1.0)(-33)	1.5±0.5	- -	-
$Cl + CO \xrightarrow{M} ClCO$	(1.3±0.5)(-33)	3.8±0.5	- -	-
$Cl + C_2H_2 \xrightarrow{M} ClC_2H_2$	(6.0±1.0)(-30)	3.5±0.5	(1.0±0.5)(-10)	2.6±0.5
$ClO + ClO \xrightarrow{M} Cl_2O_2$	(1.8±0.5)(-32)	3.6±1.0	(6.0±2)(-12)	0±1
$ClO + NO_2 \xrightarrow{M} ClONO_2$	(1.8±0.3)(-31)	3.4±1.0	(1.5±0.7)(-11)	1.9±1.9
$BrO + NO_2 \xrightarrow{M} BrONO_2$	(5.2±0.5)(-31)	3.8±1.0	(9.0±1.0)(-12)	2.3±1.0
$F + O_2 \xrightarrow{M} FO_2$	(4.4±0.4)(-33)	1.2±0.5	- -	-
$F + NO \xrightarrow{M} FNO$	(5.9±3.0)(-32)	1.7±1.7	- -	-
$F + NO_2 \xrightarrow{M} Products$	(1.1±0.6)(-30)	2.0±2.0	(3.0±2.0)(-11)	1±1
$FO + NO_2 \xrightarrow{M} FONO_2$	(2.6±2.0)(-31)	1.3±1.3	(2.0±1.0)(-11)	1.5±1.5

Table 2. (Continued)

Reaction	Low Pressure Limit[a] $k_o(T) = k_o^{300}(T/300)^{-n}$		High Pressure Limit[b] $k_\infty(T) = k_\infty^{300}(T/300)^{-m}$	
	k_o^{300}	n	k_∞^{300}	m
$CH_3 + O_2 \xrightarrow{M} CH_3O_2$	(4.5±1.5)(-31)	2.0±1.0	(1.8±0.2)(-12)	1.7±1.7
$C_2H_5 + O_2 \xrightarrow{M} C_2H_5O_2$	(2.0±1.5)(-28)	3.8±1.0	(5.0±3.0)(-12)	0±1
$CH_3O_2 + NO_2 \xrightarrow{M} CH_3O_2NO_2$	(1.5±0.8)(-30)	4.0±2.0	(6.5±3.2)(-12)	2±2
$OH + SO_2 \xrightarrow{M} HOSO_2$	(3.0±1.0)(-31)	3.3±1.5	(1.5±0.5)(-12)	$0\pm^{0}_{2}$
$OH + C_2H_4 \xrightarrow{M} HOCH_2CH_2$	(1.5±0.6)(-28)	0.8±2.0	(8.8±0.9)(-12)	$0\pm^{0}_{2}$
$OH + C_2H_2 \xrightarrow{M} HOCHCH$	(5.5±2.0)(-30)	0.0±0.2	(8.3±1.0)(-13)	$-2\pm^{2}_{1}$
$CF_3 + O_2 \xrightarrow{M} CF_3O_2$	(1.5±0.3)(-29)	4±2	(8.5±1.0)(-12)	1±1
$CFCl_2 + O_2 \xrightarrow{M} CFCl_2O_2$	(5.0±0.8)(-30)	2±2	(6.0±1.0)(-12)	1±1
$CCl_3 + O_2 \xrightarrow{M} CCl_3O_2$	(1.0±0.7)(-30)	2±2	(2.5±2)(-12)	1±1
$CFCl_2O_2 + NO_2 \xrightarrow{M} CFCl_2O_2NO_2$	(3.5±0.5)(-29)	5±1	(6.0±1.0)(-12)	2.5±1
$CF_3O_2 + NO_2 \rightarrow CF_3O_2NO_2$	(2.2±0.5)(-29)	5±1	(6.0±1.0)(-12)	2.6±1
$CCl_3O_2 + NO_2 \rightarrow CCl_3O_2NO_2$	(5.0±1.0)(-29)	5±1	(6.0±1.0)(-12)	2.5±1
$HS + NO \xrightarrow{M} HSNO$	(2.4±0.4)(-31)	3±1	(2.7±0.5)(-11)	$0\pm^{0}_{2}$
$Na + O_2 \xrightarrow{M} NaO_2$	(2.4±0.5)(-30)	1.2±0.5	(4.0±2.0)(-10)	0±1
$NaO + O_2 \xrightarrow{M} NaO_3$	(3.5±0.7)(-30)	2±2	(5.7±3)(-10)	0±1
$NaO + CO_2 \xrightarrow{M} NaCO_3$	(8.7±2.6)(-28)	2±2	(6.5±3)(-10)	0±1
$NaOH + CO_2 \xrightarrow{M} NaHCO_3$	(1.3±0.3)(-28)	2±2	(6.8±4)(-10)	0±1

Note: $k(Z) = k(M,T) = \left(\frac{k_o(T)[M]}{1 + k_o(T)[M]/k_\infty(T)}\right) 0.6^{\{1 + [\log_{10}(k_o(T)[M]/k_\infty(T))]^2\}^{-1}}$

The values quoted are suitable for air as the third body, M.

a Units are $cm^6/molecule^2$-sec

b Units are cm^3/molecule-sec

6.0 Equilibrium Constants

6.1 Format

Some of the three-body reactions in Table 2 form products which are thermally unstable at atmospheric temperatures. In such cases the thermal decomposition reaction may compete with other loss processes, such as photodissociation or radical attack. Table 3 lists the equilibrium constants, K(T), for eleven reactions which may fall into this category. The table has three column entries, the first two being the parameters A and B which can be used to express K(T):

$$K(T)/\text{cm}^3\ \text{molecule}^{-1} = A\ \exp(B/T),\ (200\ \text{K} < T < 300\ \text{K})$$

The third column entry in Table 3 is the calculated value of K at 298 K.

The data sources for K(T) are described in the individual notes to Table 3. When values of the heats of formation and entropies of all species are known at the temperature T, we note that:

$$\log(K(T)/\text{cm}^3\ \text{molecule}^{-1}) = (\Delta S^o{}_T/2.303R) - (\Delta H^o{}_T/2.303RT) + \log(T) - 21.87$$

where the superscript "o" refers to a standard state of one atmosphere. In some cases K values were calculated from this equation, using thermochemical data. In other cases the K values were calculated directly from kinetic data for the forward and reverse reactions. When available, JANAF values were used for the equilibrium constants. The following equations were then used to calculate the parameters A and B:

$$B/°K = 2.303(\log(K_{200}/K_{300}))(300\times200)/(300-200)$$

$$= 1382(\log(K_{200}/K_{300}))$$

$$\log(A) = \log(K(T)) - B/2.303T$$

Table 3. Equilibrium Constants

Reaction	A/cm^3 molecule^{-1}	B±ΔB/°K	K_{eq}(298 K)	f(298 K)[a]
$HO_2 + NO_2 \rightarrow HO_2NO_2$	2.1×10^{-27}	10,900±1,000	1.6×10^{-11}	5
$NO + NO_2 \rightarrow N_2O_3$	3.0×10^{-27}	4,700±100	2.1×10^{-20}	2
$NO_2 + NO_2 \rightarrow N_2O_4$	5.9×10^{-29}	6,600±250	2.4×10^{-19}	2
$NO_2 + NO_3 \rightarrow N_2O_5$	4.0×10^{-27}	10,930±500	3.4×10^{-11}	1.5
$CH_3O_2 + NO_2 \rightarrow CH_3O_2NO_2$	1.3×10^{-28}	11,200±1,000	2.7×10^{-12}	2
$Cl + O_2 \rightarrow ClOO$	5.7×10^{-25}	2,500±750	2.5×10^{-21}	2
$ClO + O_2 \rightarrow ClO \cdot O_2$	$<2.9\times10^{-26}$	<5,000±1,500	$<5.6\times10^{-19}$	500
$Cl + CO \rightarrow ClCO$	1.6×10^{-25}	4,000±500	1.1×10^{-19}	5
$ClO + ClO \rightarrow Cl_2O_2$	3.0×10^{-27}	8,450±850	6.2×10^{-15}	2
$ClO + OClO \rightarrow Cl_2O_3$	1.6×10^{-27}	7,200±1,400	5.0×10^{-17}	10
$F + O_2 \rightarrow FOO$	3.2×10^{-25}	6,100±1,200	2.5×10^{-16}	10

K_{eq}/cm^3 molecule^{-1} = A exp (B/T) [200 < T/K < 300]

[a] f(298 K) is the uncertainty factor in K_{eq} at 298 K. To calculate the uncertainty at other temperatures, use the expression: $f(T) = f(298\ K) \exp \left|\Delta B \left(\frac{1}{T} - \frac{1}{298}\right)\right|$.

7.0 Photochemical Data

7.1 Discussion of Format and Error Estimates

In Table 4 we present a list of photochemical reactions considered to be of stratospheric interest. The absorption cross sections of O_2 and O_3 largely determine the extent of penetration of solar radiation into the stratosphere and troposphere. Some comments and references to these cross sections are presented in the text, but only a sample of the data are listed here. (See, for example, WMO Report #11, 1982; WMO-NASA, 1985.) The photodissociation of NO in the O_2 Schumann-Runge band spectral range is another important process requiring special treatment and is not discussed in this evaluation. (See, for example, Frederick and Hudson, 1979; Allen and Frederick, 1982; and WMO Report #11, 1982.)

For some other species having highly structured spectra, such as CS_2 and SO_2, some comments are given in the text of the complete evaluation, but the photochemical data are not presented. The species CH_2O, NO_2, NO_3, ClO, BrO, and OClO also have complicated spectra but, in view of their importance for atmospheric chemistry, a sample of the data is presented in the evaluation; for more detailed information on their high-resolution spectra and temperature dependence, the reader is referred to the original literature.

Table 5 gives recommended reliability factors for some of the more important photochemical reactions. These factors represent the combined uncertainty in cross sections and quantum yields, taking into consideration the atmospherically important wavelength regions, and they refer to the total dissociation rate regardless of product identity (except in the case of $O(^1D)$ production from photolysis of O_3).

Table 4. Photochemical Reactions of Stratospheric Interest

$O_2 + h\nu \rightarrow O + O$

$O_3 + h\nu \rightarrow O_2 + O$

$O_3 + h\nu \rightarrow O_2 + O(^1D)$

$HO_2 + h\nu \rightarrow$ products

$H_2O + h\nu \rightarrow H + OH$

$H_2O_2 + h\nu \rightarrow OH + OH$

$NO + h\nu \rightarrow N + O$

$NO_2 + h\nu \rightarrow NO + O$

$NO_3 + h\nu \rightarrow$ products

$N_2O + h\nu \rightarrow N_2 + O(^1D)$

$N_2O_5 + h\nu \rightarrow$ products

$NH_3 + h\nu \rightarrow NH_2 + H$

$HNO_2 + h\nu \rightarrow OH + NO$

$HNO_3 + h\nu \rightarrow OH + NO_2$

$HNO_4 + h\nu \rightarrow$ products

$Cl_2 + h\nu \rightarrow Cl + Cl$

$ClO + h\nu \rightarrow Cl + O$

$ClOO + h\nu \rightarrow$ products

$OClO + h\nu \rightarrow O + ClO$

$ClO_3 + h\nu \rightarrow$ products

$Cl_2O_2 + h\nu \rightarrow$ products

$HCl + h\nu \rightarrow H + Cl$

$HOCl + h\nu \rightarrow OH + Cl$

$ClNO + h\nu \rightarrow Cl + NO$

$ClNO_2 + h\nu \rightarrow$ products

$ClONO + h\nu \rightarrow$ products

$ClONO_2 + h\nu \rightarrow$ products

$CCl_4 + h\nu \rightarrow$ products

$CCl_3F + h\nu \rightarrow$ products

$CCl_2F_2 + h\nu \rightarrow$ products

$CHClF_2 + h\nu \rightarrow$ products

$CH_3Cl + h\nu \rightarrow$ products

$CH_3CF_2Cl + h\nu \rightarrow$ products

$CF_3CHCl_2 + h\nu \rightarrow$ products

$CF_3CHFCl + h\nu \rightarrow$ products

$CH_3CFCl_2 + h\nu \rightarrow$ products

$CH_3CCl_3 + h\nu \rightarrow$ products

$CBrF_3 + h\nu \rightarrow$ products

$CF_2Br_2 + h\nu \rightarrow$ products

$CBrClF_2 + h\nu \rightarrow$ products

$CF_2BrCF_2Br + h\nu \rightarrow$ products

$CF_4 + h\nu \rightarrow$ products

$C_2F_6 + h\nu \rightarrow$ products

$SF_6 + h\nu \rightarrow$ products

$CCl_2O + h\nu \rightarrow$ products

$CClFO + h\nu \rightarrow$ products

$CF_2O + h\nu \rightarrow$ products

$BrO + h\nu \rightarrow Br + O$

$BrONO_2 + h\nu \rightarrow$ products

$HF + h\nu \rightarrow H + F$

$CO + h\nu \rightarrow C + O$

$CO_2 + h\nu \rightarrow CO + O$

$CH_4 + h\nu \rightarrow$ products

$CH_2O + h\nu \rightarrow$ products

$CH_3OOH + h\nu \rightarrow$ products

$HCN + h\nu \rightarrow$ products

$CH_3CN + h\nu \rightarrow$ products

$SO_2 + h\nu \rightarrow SO + O$

$OCS + h\nu \rightarrow CO + S$

$H_2S + h\nu \rightarrow HS + H$

$CS_2 + h\nu \rightarrow$ products

$NaCl + h\nu \rightarrow Na + Cl$

$NaOH + h\nu \rightarrow Na + OH$

Table 5. Combined Uncertainties for Cross Sections and Quantum Yields

Species	Uncertainty
O_2 (Schumann-Runge bands)	1.4
O_2 (Continua)	1.3
O_3	1.1
$O_3 \rightarrow O(^1D)$	1.4
NO_2	1.3
NO_3	2.0
N_2O	1.2
N_2O_5	2.0
H_2O_2	1.4
HNO_3	1.3
HO_2NO_2	2.0
CH_2O	1.4
HCl	1.1
HOCl	1.4
$ClONO_2$	1.3
CCl_4	1.1
CCl_3F	1.1
CCl_2F_2	1.1
CH_3Cl	1.1
CF_2O	2.0
CH_3OOH	1.8
$BrONO_2$	1.4
CF_3Br	2.0
CF_2ClBr	3.0
CF_2Br_2	3.0
$C_2F_4Br_2$	3.0

SECTION D

APPENDIX

GAS PHASE ENTHALPY DATA

The following data are adapted mainly from CODATA (1984), although a few entries have been updated.

MOLECULE	$\Delta H_f(298)$ (Kcal/mol)	MOLECULE	$\Delta H_f(298)$ (Kcal/mol)	MOLECULE	$\Delta H_f(298)$ (Kcal/mol)	MOLECULE	$\Delta H_f(298)$ (Kcal/mol)
H	52.1	CH_3OH	-48.2	F_2	0.00	CH_3Cl	-19.6
H_2	0.00	CH_3OOH	-31.3	HF	-65.34	$ClCO$	-5±1
O	59.57	CH_3ONO	-15.6	HOF	-23.4±1	$COCl_2$	-52.6
$O(^1D)$	104.9	CH_3ONO_2	-28.6	FO	26±5	$CHFCl$	-14.5±2
O_2	0.00	$CH_3O_2NO_2$	-10.6±2	F_2O	5.9±.4	CH_2FCl	-63±2
$O_2(^1\text{-DELTA})$	22.5	C_2H	135.0	FO_2	6±2	$CFCl$	7±6
$O_2(^1\text{-SIGMA})$	37.5	C_2H_2	54.35	F_2O_2	5±2	$CFCl_2$	-22±2
O_3	34.1	C_2H_3	68.1	$FONO$	-15±7	$CFCl_3$	-68.1
HO	9.3	C_2H_4	12.45	FNO	-16±2	CF_2Cl	-64±3
HO_2	3±1	C_2H_5	28.4	FNO_2	-26±2	CF_2Cl_2	-117.9
H_2O	-57.81	C_2H_6	-20.0	$FONO_2$	2.5±7	CF_3Cl	-169.2
H_2O_2	-32.60	CH_2CN	58.6	CF_2	-44±2	$CHFCl_2$	-68.1
N	113.00	CH_3CN	19.1	CF_3	-112±1	CHF_2Cl	-115.6
N_2	0.00	CH_2CO	-14.23	CF_4	-223.0	$COFCl$	-102±2
NH	82.0	CH_3CO	-5.8	CHF_3	-166.8	CH_2CF_3	-124±2
NH_2	45.3	CH_3CHO	-39.7	CHF_2	-58±2	CH_3CF_2	-72±2
NH_3	-10.98	C_2H_5O	-4.1	CH_2F_2	-107.2	CH_3CF_3	-178
NO	21.57	CH_2CH_2OH	-13±2	CH_2F	-8±2	CF_2CF_3	-213
NO_2	7.9	C_2H_5OH	-56.2	CH_3F	-55.9±1	CHF_2CF_3	-264
NO_3	17±2	CH_3CO_2	-49.6	FCO	-41±14	C_2Cl_4	-3.0
N_2O	19.61	$C_2H_5O_2$	-4±3	COF_2	-151.7	C_2HCl_3	-1.9
N_2O_3	19.8	CH_3OOCH_3	-30.0	Cl	28.9	CH_2CCl_3	11±7
N_2O_4	2.2	C_3H_5	39.4	Cl_2	0.00	CH_3CCl_3	-34.0
N_2O_5	2.7±2	C_3H_6	4.8	HCl	-22.06	CH_2CH_2Cl	19.3±2
HNO	23.8	$n\text{-}C_3H_7$	22.6±2	ClO	24.4	Br	26.7
$HONO$	-19.0	$i\text{-}C_3H_7$	19±2	$ClOO$	23±1	Br_2	7.39
HNO_3	-32.3	C_3H_8	-24.8	$OClO$	23±2	HBr	-8.67
HO_2NO_2	-11±2	C_2H_5CHO	-44.8	$ClOO_2$	>13.4	$HOBr$	-19±2
C	170.9	CH_3COCH_3	-51.9	ClO_3	37	BrO	30
CH	142.0	S	66.22	Cl_2O	19.5	$BrNO$	19.7
CH_2	92.3	S_2	30.72	Cl_2O_2	31±3	$BrONO$	25±7
CH_3	35.1	HS	34±1	Cl_2O_3	33±3	$BrONO_2$	12±5
CH_4	-17.88	H_2S	-4.9	$HOCl$	-18.6±3	$BrCl$	3.5
CN	104.0	SO	1.2	$ClNO$	12.4	CH_2Br	40±2
HCN	32.3	SO_2	-70.96	$ClNO_2$	3.0	$CHBr_2$	45±2
CH_3NH_2	-5.5	SO_3	-94.6	$ClONO$	20±7	CH_2Br_2	-2.6±2
NCO	38	HSO	1±3	$ClONO_2$	6.3	CH_3Br	-8.5
CO	-26.42	HSO_3	-92±2	FCl	-12.1	I	25.52
CO_2	-94.07	CS	65	CCl	120±5	I_2	14.92
HCO	9.0	CS_2	28.0	CCl_2	57±5	HI	6.3
CH_2O	-26.0	CH_3S	33±2	CCl_3	18±1	CH_3I	3.5
$COOH$	-50±2	CH_3SH	-5.5	CCl_4	-22.9	CH_2I	54.9±2
$HCOOH$	-90.5	CH_3SCH_3	-8.9	$CHCl_3$	-24.6	IO	41.1
CH_3O	3.5	CH_3SSCH_3	-5.8	$CHCl_2$	23±2	INO	29.0
CH_3O_2	5±2	OCS	-34	CH_2Cl	29±2	INO_2	14.4
CH_2OH	-6.2	F	18.98	CH_2Cl_2	-22.8		

SECTION E

An Assessment of the Impact on Stratospheric Chemistry and Ozone caused by the Launch of the Space Shuttle and Titan IV

Michael J. Prather and Maria M. Garcia
NASA, Goddard Institute for Space Studies, New York, NY

Anne R. Douglass and Charles H. Jackman,
NASA, Goddard Space Flight Center, Greenbelt, MD

Malcolm K. W. Ko and Nien Dak Sze,
Atmospheric and Environmental Research Inc., Cambridge, MA

1.0 INTRODUCTION

The launch of NASA's Space Shuttle and similar rockets injects chlorine compounds directly into the stratosphere, adding to the current burden of stratospheric chlorine. Depletion of the stratospheric ozone layer has been linked to increases in stratospheric chlorine compounds associated predominantly with chlorofluorocarbons (see recent assessments, NASA/WMO, 1986; Watson et al., 1988; UNEP/WMO, 1990). The purpose of this study is to determine the magnitude of the chlorine increases that might be caused by the Space Shuttle and to assess the overall impact on the chemistry and composition of the global stratosphere.

The solid rocket motors on the Space Shuttle and Titan IV launch vehicles use a solid fuel composed of ammonium perchlorate, aluminum and a polymer binder (Peter Evanoff, Thiokol Corp., private communication, 1989). The exhaust consists primarily of gaseous HCl, carbon monoxide, water vapor, molecular nitrogen and aluminum oxide. The last assessment of the Shuttle in terms of stratospheric ozone was more than a decade ago (Potter, 1978), and our understanding of stratospheric chemistry and modelling has evolved much since then.

The launch scenario considered here consists of 9 Shuttles and 6 Titans per year. It is typical of the current schedule, but it may fall short of the frequency needed for major space projects. The chlorine from these launches is used as a stratospheric source of Cl_y (total inorganic chlorine: the sum of HCl, Cl, Cl_2, ClO, $ClONO_2$ and HOCl) in three numerical models of the stratosphere. Calculations have been made with two two-dimensional (latitude by altitude) models with complete chemistry (AER: Ko et al., 1985, 1989; GSFC: Douglass et al., 1989, Jackman et al., 1989a) and a three-dimensional model for chemical tracers (GISS: Prather et al., 1990).

In one numerical simulation, Cl_y enhancements in the middle stratosphere two days after a January launch of the Shuttle are still expected to be clumpy, but the exhaust plume is predicted to have spread over a region about 20° latitude by 30° longitude with an average increase of about 30 ppt (parts per 1012) or 2% above background. One month later the Shuttle plume is well mixed, and increases in Cl_y are less than 4 ppt throughout the stratosphere. The buildup of chlorine from these launches approaches a steady-state limit after several years; on average, Cl_y would increase by about 10 ppt in the middle stratosphere of the northern hemisphere, less than 0.5% above current levels. Corresponding ozone depletions are predicted to be less than 0.2% locally, with smaller perturbations to the ozone column.

The profiles and amounts of chlorine injected from the solid rocket motors are summarized in section 2. The transient response to a single launch is shown in section 3, and model predictions of the steady-state accumulation of Cl_y are described in section 4. The overall impact on stratospheric chemistry and ozone is discussed in section 5.

2.0 SOURCE OF CHLORINE FROM ROCKET EXHAUST

Estimates of the amount and distribution of chlorine released from the launch of the NASA Space Shuttle and the Titan IV expendable launch vehicle are available from Thiokol (Peter D. Evanoff, private communication, 1989). In Table 1 we report the kg of chlorine (as Cl) released in 5 km vertical intervals for Shuttle launches from Cape Canaveral, Florida (9 per yr) and for Titan IV launches from both Cape Canaveral (4 per yr) and Vandenberg Air Force Base, California (2 per yr). The chlorine is released as HCl which we treat as Cl_y in the models.

Table 1. Stratospheric Chlorine Released Annually by Shuttle/Titan IV Launches

Altitude	kg of chlorine (Cl)		
		location:	
	29°N 80°W	29°N 80°W	34°N 121°W
15-20 km	176,800	16,800	8,400
20-25 km	136,100	14,700	7,300
25-30 km	109,600	12,600	6,300
30-35 km	87,400	10,600	5,300
35-40 km	69,300	8,900	4,500
40-45 km	25,900	7,300	3,700
45-50 km	4,500	6,000	3,000

The launch scenario assumes 9 Shuttles and 4 Titans from Cape Canaveral, Florida (29°N 80°W) and 2 Titans from Vandenberg AFB, California (34°N 121°W).

The total amount of chlorine released into the stratosphere (above 15 km) by the solid rocket motors is 725,000 kg (0.725 kilotons) per year, and can be compared with that associated with industrial halocarbons. The chemical industry's production of halocarbons exceeds 1,250 kilotons of chlorine per yr (see UNEP/WMO, 1990). The release of chlorine during photochemical destruction of the chlorofluorocarbons (CFCs) occurs predominantly in the stratosphere, but happens slowly, on time scales of order 100 yr, over the lifetime of the gas. The estimated annual source of stratospheric chlorine from the industrial halocarbons is about 300 kilotons of chlorine per yr (AER model); the remainder of the annual emissions goes into the accumulating atmospheric burden of chlorinated halocarbons (about 600 kt/yr) or is destroyed in the troposphere. Thus, the launch schedule in Table 1 would add only about 0.25% to the current stratospheric source of Cl_y.

The release of chlorine from the 15 launches summarized in Table 1 was averaged over the year and put into the models as a continuous source of Cl_y every time step. The vertical distribution specified in Table 1 was used by the models. The latitudinal location of the two launch sites was included in all three models, but the longitudinal location could only be specified in the 3-D simulation.

3.0 TRANSIENT RESPONSE TO A SINGLE SHUTTLE LAUNCH

One launch of the Space Shuttle injects a single, very large pulse of 68,000 kg of chlorine into the stratosphere. Although this amount of chlorine is inconsequential on a globally averaged scale, the greatly enhanced levels of Cl_y in the vicinity of the exhaust plume may lead to large ozone depletions over a spatially limited region. We examined the transient response of stratospheric Cl_y to a single Shuttle launch using the 3-D GISS model. The chlorine is released over Cape Canaveral (29°N, 80°W) by using one-ninth of the annual source given in Table 1 as an instantaneous source.

Simulations were initiated on January 1 and July 1, and continued for one month. Immediately following the launch, the exhaust plume will not be completely mixed over the scales resolved by the model grid, and the calculations are intended to represent the average concentration of the resulting non-uniform distribution. Figures 1 and 2 summarize the instantaneous increase in Cl_y concentrations at 3.4 mbar (about 40 km altitude) as a function of latitude and longitude for days 2(a), 4(b), 8(c) and 30(d) following both the January and July initializations. Other levels in the upper stratosphere show similar effects, but lower altitudes in the stratosphere have smaller absolute enhancements of Cl_y (see Figures 3-5).

After two days (Figures 1a & 2a), the average increase in chlorine in the upper stratosphere, 50 ppt (January) and 70 ppt (July), is localized near the launch site with peak levels not resolved by the model grid (8° latitude by 10° longitude). After eight days (Figures 1c & 2c), the maximum grid-averaged levels have decreased by factors of about four (January) and two (July), have moved away from the launch site in accord with the prevailing winds, and have spread over horizontal scales that are resolved by the model. For the January launch most of the added chlorine (concentrations greater than 1 ppt) resides in the region bounded by 20°N-50°N and 40°W-100°W. The summer stratosphere is less dispersive, and for the July launch most of the Cl_y is contained between 20°N-36°N and 150°E-140°W. Eight days after the January 1 launch (Figure 1c) the largest grid-averaged perturbation to Cl_y (as resolved by the model grid) is less than 10 ppt, about 0.4% above background levels. Eight days after the July launch (Figure 2c) the added Cl_y remains more concentrated, greater than 30 ppt (about 1%) above background over a smaller area.

One month after the Shuttle launch (Figures 1d & 2d), the added chlorine is predicted to have spread over most of the upper stratosphere in the northern hemisphere, and the plume is expected to have mixed thoroughly. The winter stratosphere is dispersive and Cl_y perturbations are less than 1 ppt everywhere. In summer, the exhaust products remain predominantly over midlatitudes (20°N-50°N) with perturbations still as large as 3 ppt. The globally averaged depletion of ozone associated with a single launch should be less than that caused by the steady-state buildup of chlorine, as discussed below. Local destruction of ozone in the immediate vicinity of the rocket plume could be significantly larger and is not explicitly resolved in these global models.

4.0 STEADY-STATE ACCUMULATION OF STRATOSPHERIC CHLORINE

The three models used the continuous source of stratospheric chlorine from the rocket launches as described in section 2. The ultimate removal for the injected stratospheric Cl_y is transport into the lower atmosphere (troposphere) where most inorganic chlorine species are soluble and therefore removed rapidly by rainfall and other processes. In these models, this sink was applied by imposing either rapid loss for Cl_y below 10 km (2-D models) or a negligibly small concentration of Cl_y below 1 km (3-D model). Small differences in the application of this lower boundary condition do not affect the calculated stratospheric Cl_y distribution, because almost all of the chlorine transported into the troposphere is removed and cannot be recirculated back into the stratosphere.

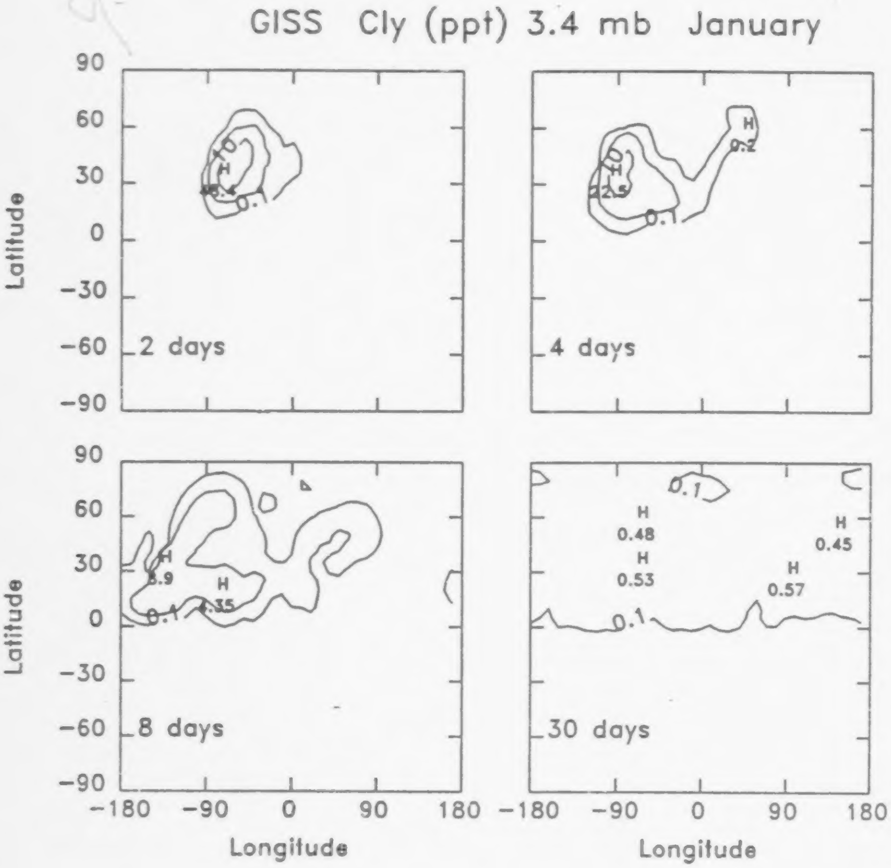

Figure 1. Latitude by longitude contours of chlorine enhancements near 40 km altitude due to a single Shuttle launch on January 1. Results from the GISS model are shown for (a) 2, (b) 4, (c) 8 and (d) 30 days following the launch.

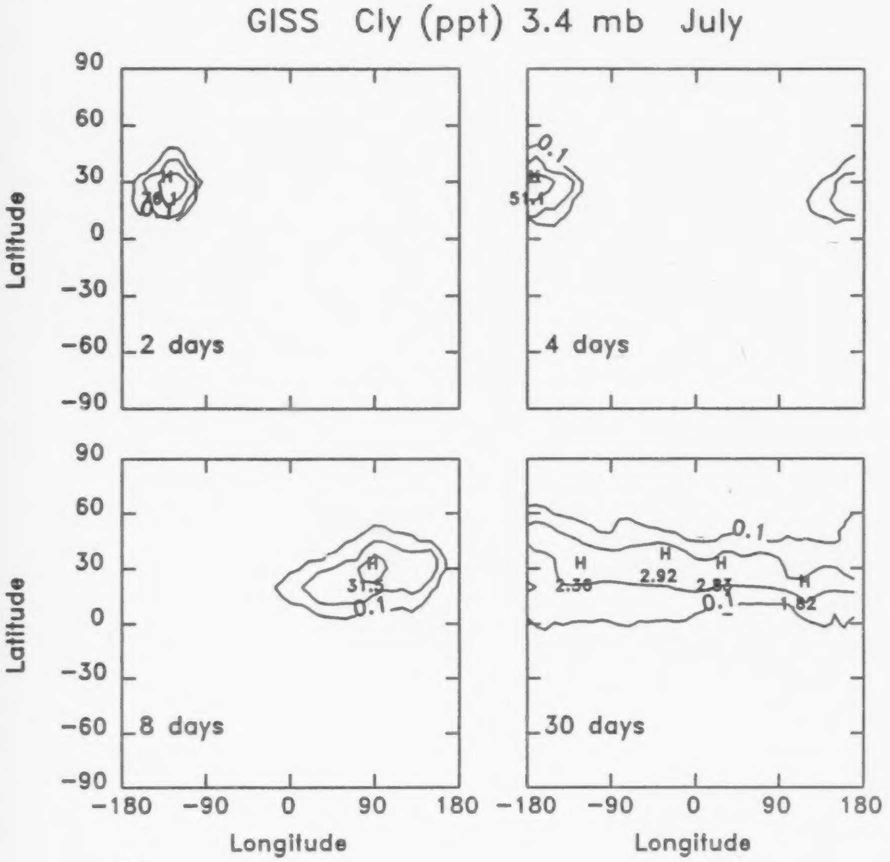

Figure 2. Latitude by longitude contours of chlorine enhancements due to a single Shuttle launch on July 1. See Figure 1.

These calculations were initiated and then continued for several model years until a steady-state distribution was reached. In steady state, stratospheric Cl_y additions have built up until the amount of chlorine injected into the stratosphere equals that transported into the lower troposphere.

The computed addition to Cl_y (ppt) associated with the Shuttle/Titan launches is shown as monthly, zonal averages in Figures 3-5 for the GSFC, AER and GISS models, respectively. The magnitudes of the Cl_y increase is largest in northern midlatitudes (30°N-50°N) near the source, and peaks in the upper stratosphere (30-45 km altitude) where the rocket emissions are largest on a molecule per molecule of air basis. Increased concentrations of Cl_y in the northern upper stratosphere range from 6 to 14 ppt in the GSFC model (Figure 3), 4 to 9 ppt in the AER model (Figure 4) and 6 to 12 ppt in the GISS model (Figure 5). The GSFC and GISS models predict a similar buildup of Cl_y; the AER model appears to have a more rapid stratospheric circulation (see Jackman et al., 1989b) that flushes out the chlorine more rapidly. In the lower stratosphere (15-25 km altitude) Cl_y concentrations are less enhanced: about 2 ppt at 15 km increasing to about 6 ppt at 25-km. Several years are required to transport substantial concentrations of the rocket source of Cl_y into the southern hemisphere stratosphere. Enhancements in the southern stratosphere range from less than 1 to as much as 6 ppt, and are generally a factor of 2 or greater below the corresponding enhancements in the northern stratosphere.

During northern winter, all models show rapid northward mixing between 30°N and the Pole, with isolines that slant poleward and downward. This basic pattern shown in Figures 3a-5a is typical of other long-lived stratospheric tracers, both from model calculations (see Jackman et al., 1989b) and observations (see NASA/WMO, 1986). The pattern of Cl_y during northern summer, however, dramatically shows the impact of a localized stratospheric source in a season without substantial latitudinal mixing. The increases in Cl_y concentration in July (Figures 3b-5b) peak strongly at 30°N between 30 and 50 km altitude in all three models, with monthly and zonally averaged maxima of more than 12 ppt in the GSFC and GISS models, and 9 ppt in the AER model.

In order to determine the relative perturbation to Cl_y from the rocket launches, the 2-D models compared the calculated Cl_y enhancements (Figures 3-4) with the Cl_y calculated from all other sources, the CFCs, CCl_4, CHF_2Cl, CH_3CCl_3, CH_3Cl. Air enters the stratosphere containing a mix of these halocarbons representing the bulk tropospheric mixing ratios of these species and with negligible concentrations of the more soluble inorganic chlorine (Cl_y). In the lower stratosphere, Cl_y concentrations are small because only a fraction of the CFCs have been photochemically destroyed, thereby releasing chlorine atoms. In the upper stratosphere where the halocarbon and CFC concentrations are greatly reduced, Cl_y concentrations approach their upper limit, currently about 3 ppb (parts per 10^9). The scenario for rocket launches in Table 1 leads to only modest perturbations in stratospheric Cl_y, as shown in Figures 6 (GSFC) and 7 (AER). The GSFC results predict increases ranging from 0.3 to 0.6% over the northern midlatitudes; while the AER model gives smaller enhancements, 0.2 to 0.3%. In the southern hemisphere, Cl_y increases are less than 0.2% for the GSFC model and 0.1% for the AER model.

Ozone perturbations at steady state associated with the source of Cl_y from rocket launches are shown in Figure 8 for the GSFC model. The largest depletions in ozone concentration, between 0.10% and 0.15%, occur in the upper stratosphere (30-45 km altitude) in the northern midlatitudes. Losses elsewhere are much smaller with the exception of the corresponding locations in the southern hemisphere. The depletion of the total column abundance of ozone is likewise small, less than 0.1%. The photochemical model used here includes only gas-phase, homogeneous chemical reactions; it does not account for the heterogeneous reactions occurring on polar stratospheric clouds that have been shown to be responsible for the chlorine-catalyzed destruction of ozone in the lower stratosphere during polar winter (the Antarctic ozone hole).

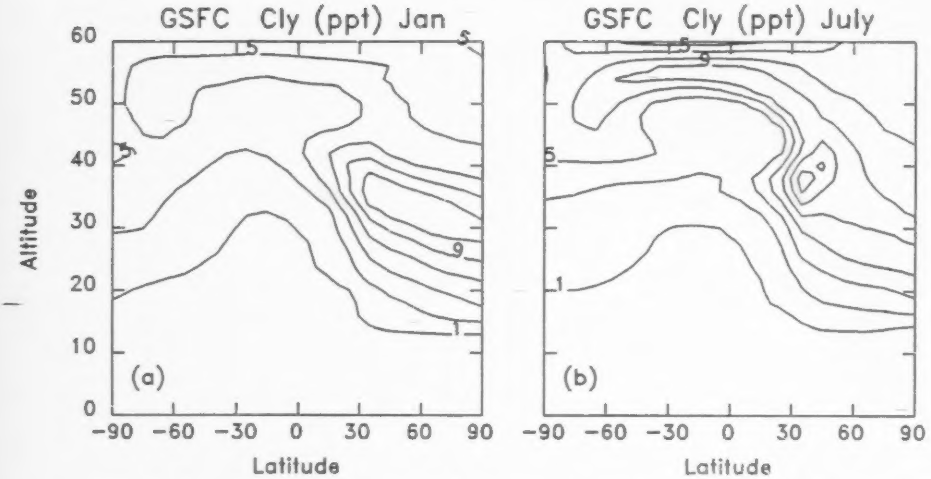

Figure 3. Latitude by altitude (pressure) contours of enhanced chlorine (in ppt) from the GSFC model. The steady-state buildup of chlorine as Cly is caused by the launch of 9 Shuttles and 6 Titan IV vehicles per year. The monthly and zonally averaged concentrations are shown for (a) January and (b) July.

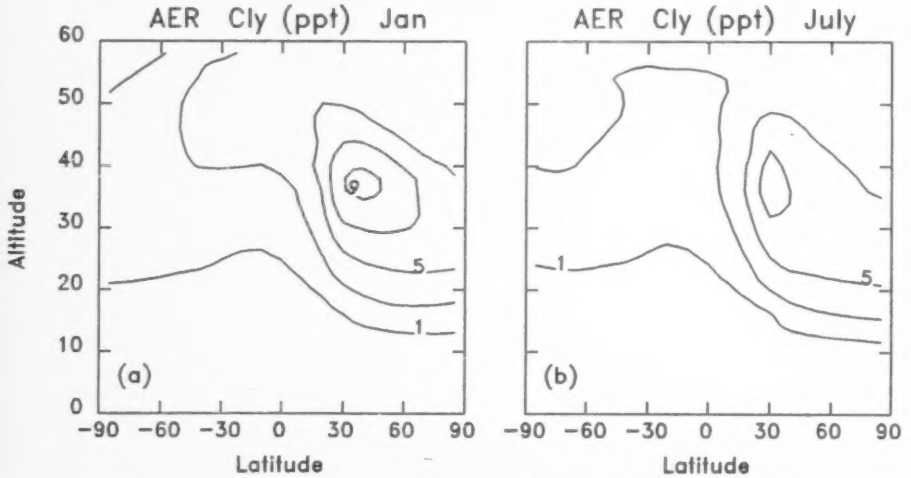

Figure 4. Latitude by altitude (pressure) contours of enhanced chlorine (in ppt) from the AER model. The steady-state buildup of chlorine as Cly is caused by the launch of 9 Shuttles and 6 Titan IV vehicles per year. The monthly and zonally averaged concentrations are shown for (a) January and (b) July.

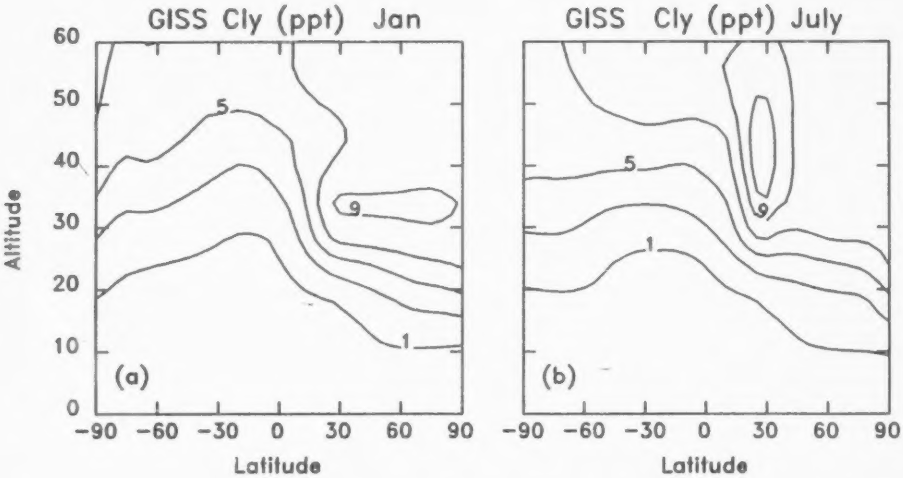

Figure 5. Latitude by altitude (pressure) contours of enhanced chlorine (in ppt) from the GISS model. The steady-state buildup of chlorine as Cl_y is caused by the launch of 9 Shuttles and 6 Titan IV vehicles per year. The monthly and zonally averaged concentrations are shown for (a) January and (b) July.

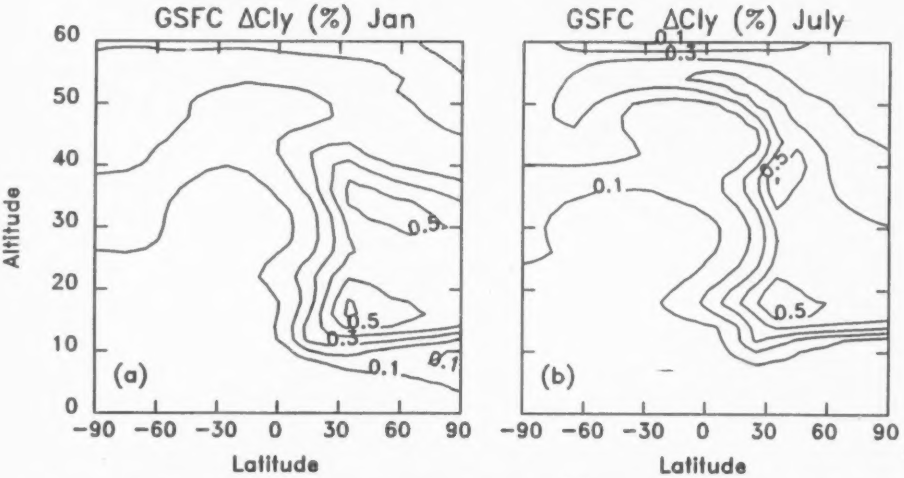

Figure 6. Latitude by altitude (pressure) contours of the perturbation to background Cl_y levels (%) from the GSFC model. The steady-state buildup of chlorine as Cly is caused by the launch of 9 Shuttles and 6 Titan IV vehicles per year. The monthly and zonally averaged concentrations are shown for (a) January and (b) July.

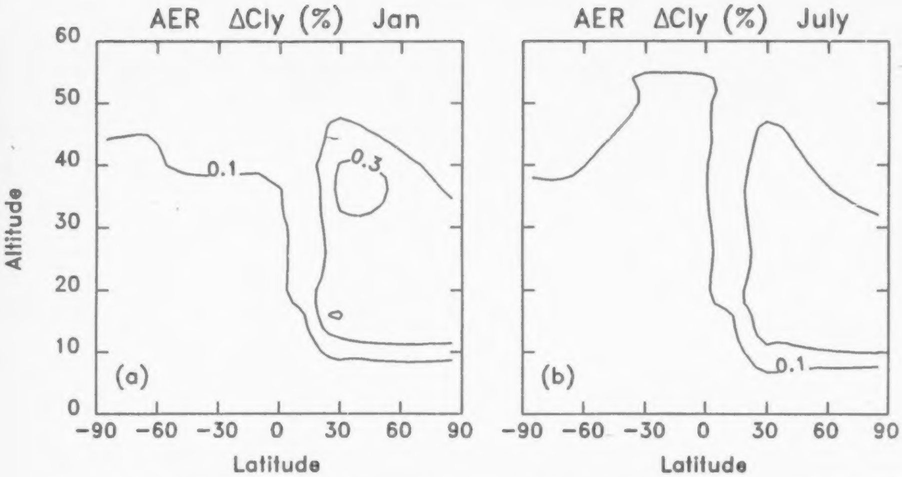

Figure 7. Latitude by altitude (pressure) contours of the perturbation to background Cl_y levels (%) from the AER model. The steady-state buildup of chlorine as Cl_y is caused by the launch of 9 Shuttles and 6 Titan IV vehicles per year. The monthly and zonally averaged concentrations are shown for (a) January and (b) July.

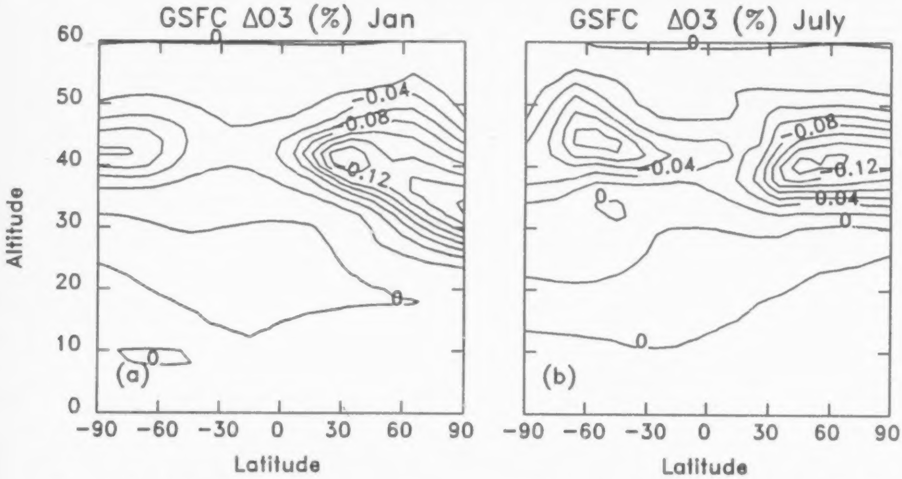

Figure 8. Latitude by altitude (pressure) contours of the perturbation to ozone (%) from the GSFC model. The steady-state buildup of chlorine as Cl_y is caused by the launch of 9 Shuttles and 6 Titan IV vehicles per year. The monthly and zonally averaged concentrations are shown for (a) January and (b) July.

Nevertheless, the impact of Shuttle chlorine on further polar ozone loss can probably be constrained since the relative perturbations to Cl_y in the lower stratosphere are less than 0.1% over Antarctica and 0.5% over the Arctic.

5.0 SUMMARY AND CONCLUSIONS: The Potential for Ozone Depletion

Each launch of the Space Shuttle injects about 0.068 kilotons of chlorine into the stratosphere. This amount is small compared to the current background of stratospheric chlorine (3 ppb), which is generated from the photochemical destruction of industrial and natural halocarbons within the stratosphere at a rate of about 300 kilotons per year. Global stratospheric models are used here to assess the impact of the currently modest launch schedule on stratospheric chemistry and ozone depletion.

In the immediate exhaust plume of the Shuttle (about 40 m across in the upper stratosphere), concentrations of HCl are large, about 0.08 by volume. Even if this plume were mixed over a 10 x 10 km area, concentrations would still exceed 1000 ppb. However, a 100 km^2 area comprises less than 1/1,000,000 of the midlatitude stratosphere, and the global or even regional effects of complete ozone destruction within this corridor would be inconsequential. Furthermore, the chlorine is released predominantly as HCl and would need some time to be chemically processed into more catalytically active forms (Cl or ClO). The path of the Shuttle is not vertically aligned, the corridor of exhaust gases is spread over lateral extent of more than a 1000 km in a day, and thus no local hole in column ozone could occur above the launch site.

This early stage following the launch is not adequately modeled in these calculations, but we believe that strict limits can be placed on the potential for global ozone destruction because the amount of chlorine injected is small compared with that contained in a 1000 km by 1000 km region (less than 0.2 ppb out of more than 2 ppb Cl_y). In order to have a significant impact on ozone globally, the plume must mix with the stratospheric environment and lead to significant perturbations over scales of at least 1000 x 1000 km.

In the few days following a launch, stratospheric winds will have stretched and dispersed the exhaust plume to scales greater than 1000 km. The average increase in stratospheric chlorine levels over such an area is modest, at most +5% within a 20° latitude by 20° longitude area. By the end of the month, these perturbations decrease rapidly to less than 0.2% above background levels as the chlorine is mixed laterally throughout the stratosphere.

A continuous series of rocket launches will lead to a buildup of chlorine in the stratosphere whose magnitude is governed by the frequency of launches and the rate of the stratosphere-troposphere circulation. For a scenario of 9 Shuttle and 6 Titan IV launches per year, the accumulation of chlorine in the stratosphere is still modest, ranging from 0.2 to 0.6% over northern midlatitudes and much less in the tropics and southern hemisphere. Corresponding ozone depletions are even smaller, less than 0.25% locally and less than 0.1% in the total column.

The addition of Cl_y to the winter polar stratosphere is of particular interest because of the role that chlorine plays in creating the Antarctic ozone hole, but the expected buildup at the poles represents only a small fractional increase to current levels. In the future, we might hope that stringent controls on industrial production of halocarbons, as envisaged by the Montreal Protocol, would reverse the current trend and lead to lower background levels of Cl_y. Even the most optimistic controls over halocarbons would not lead to Cl_y concentrations less than 2 ppb much before the end of the 21st century.

The Shuttle and Titan IV solid rocket motors comprise the largest source of stratospheric chlorine that is expected from the current space fleet. The major launch vehicles from the U.S. and other space agencies use non-chlorinated (e.g., liquid) fuels or employ much smaller rockets. The U.S. strategic nuclear arsenal uses solid fuel containing chlorine, but in such launches most of the chlorine would be released below 15 km.

The exhaust from the solid rocket motors also contains other possible stratospheric pollutants. The major gaseous components are CO (24% by wt), HCl (21%), H_2O (10%), N_2 (9%), CO_2 (4%) and H_2 (2%). The perturbation to CO should be about the same in mixing ratio as that to Cl_y, and would not significantly affect the background levels of order 100 ppb. Clearly the HCl represents the largest fractional perturbation to the background stratosphere; the remaining effluents should have negligible impact on the stratosphere.

Another principal exhaust product, particulate Al_2O_3 (30%), has the potential to perturb stratospheric chemistry. Most of the alumina is reported to form particles of radii greater than 1 micron; these fall out of the stratosphere more rapidly than the gaseous products which are removed by the circulation exchanging air between the stratosphere and troposphere (modeled here). The abundance of the larger alumina particles appears to be increasing (Zolensky et al., 1989) and has been attributed to solid rocket motors as well as space debris. However, some atmospheric measurements (Cofer et al., 1985) indicate that a significant fraction of the mass is in particles with radii of about 0.1 micron and thus would accumulate in a manner similar to Cl_y in these calculations. Alumina particles may act as ice deposition nuclei in the lower stratosphere (Turco et al., 1982). Observational evidence (Cofer et al., 1984) and laboratory studies suggest that alumina particles react with the HCl in the exhaust to form chlorides and may provide active sites for Cl_y-NO_y heterogeneous reactions in the lower stratosphere. Thus the buildup of small particles in the lower stratosphere may enhance both precipitation (dehydration or denitrification) and ozone destruction in the lower stratosphere. The role of particulates from solid rocket motors in the chemistry of the stratosphere is not well characterized today, and further research will be needed for a reliable assessment of future impacts.

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SECTION F

The Atmospheric Effects of Stratospheric Aircraft: Modeling and Measurements in Support of the High-Speed Research Program

(Appendix A to NRA-89-OSSA-16)

INTRODUCTION

The growth in commercial aviation is rapid and expected to continue into the next century. The desire for faster civil aircraft has long been recognized, and supersonic transports (SST's) were first proposed and studied more than two decades ago. The emissions from aircraft, both the current subsonic fleet and the projected supersonic fleet, are expected to perturb the chemical and physical environment in which they are emitted. The chemical perturbations expected from aircraft emissions include the enhancement in concentrations of odd-nitrogen compounds ($NOx = NO + NO_2$) and water vapor, and the subsequent photochemical perturbations to ozone. The magnitude of atmospheric effects is uncertain and may range from local impacts in preferred flight corridors to global perturbations through long- range atmospheric transport of emissions.

In order to assess the atmospheric impact of a fleet of commercial supersonic aircraft that cruise predominantly in the stratosphere, it is necessary to develop a scientifically sound understanding of the many perturbations that may result. It has been recognized in previous assessments of stratospheric aircraft (CIAP Report of Findings, A.J. Grobecker et al., eds., Climate Impact Assessment Program, DOT-TST-75-58, December 1974) that emissions of NO_x- and H_2O in the stratosphere may lead to ozone loss and possibly global climate change. The goal of this research program is not to determine what levels of aircraft emissions and ozone loss are environmentally acceptable, but rather more simply to determine what atmospheric effects may be expected for given levels of engine technology and operations.

In making the assessment of possible atmospheric changes caused by a fleet of stratospheric aircraft, it must be remembered that these perturbations are not occurring in isolation or in a static atmosphere. The atmosphere is currently evolving. Trace gases such as methane, nitrous oxide, and the halocarbons are expected to increase substantially (>20 %) over the next several decades. Furthermore, the proposed development of supersonic aircraft would affect all of civil aviation, including the projected operations of the subsonic fleet. Any assessment of the supersonic aircraft fleet must take into account such interactions in a framework of overall global change.

This assessment of stratospheric aircraft cannot be completed with the current global chemistry models since we recognize many areas of uncertainty in these models. The possible sources of error in the global models make it difficult to quantify accurately the perturbations caused by additional aircraft emissions.

OBJECTIVES

We shall, therefore, sponsor a focussed program of atmospheric research. This research shall be directed toward calculating the global impact of atmospheric emissions, and particularly that of stratospheric aircraft on ozone. A fundamental requirement of the program will be the capability of modeling the global atmospheric chemistry in response to a series of aircraft emission scenarios. These models, designated assessment models here, will be used on a regular basis to compare the relative impact of a set of projected emission scenarios. The assessment models must be improved along with the parallel research in this program, and they must be maintained as among the best scientific models for global atmospheric chemistry. Furthermore, specific research topics involving the modeling and measurement of fundamental chemical and dynamical processes in the stratosphere and troposphere will be supported.

A primary objective of the program is that there be annual progress in improving and validating the chemical transport models (CTM's), and hence, to reduce the uncertainties in current assessments. Based on the model predictions resulting from this program, it may be possible to optimize the emissions and operations of future aircraft fleets in order to minimize, and possibly avoid detrimental impacts on the atmosphere.

PROGRAM ELEMENTS

The following topics of research are important components of the High-Speed Research Program (HSRP), and we invite proposals that address one or more of these components:

1. Global chemical models for stratospheric ozone

The overall assessment of the atmospheric impact of stratospheric aircraft will be made with multidimensional global models of stratospheric chemistry and dynamical transport (CTM's). At present, these CTM's are represented by the basic two-dimensional zonally averaged models that have been used to predict perturbations to stratospheric ozone caused by increasing levels of chlorofluorocarbons (R.T. Watson et al., Present State of Knowledge of the Upper Atmosphere 1988: An Assessment Report, NASA Ref. Pub. 1208, August 1988). The 2-D stratospheric models will provide the basic assessment capability for the High-Speed Research Program in the near future. Within the next five years, it is expected that three-dimensional CTM's, currently supported by the Upper Atmosphere Program, will also be able to contribute to the prediction of stratospheric ozone perturbations. The assessment models are the basic tools with which to evaluate the impact of different scenarios of aircraft emissions; they can be used in sensitivity studies to choose between alternative scenarios for operations or emissions.

Preliminary simulations with the current assessment models using a range of typical aircraft emission scenarios show some interesting features: (1) perturbations are highly seasonal with chemical losses of ozone peaking at mid and high latitudes in summer; (2) the ozone decrease is very sensitive to the altitude of injection, with dramatically larger loss when cruise altitude is raised from 19 to 21 km (maximum impact on column ozone occurs for injections between 23-28 km); and (3) the stratospheric response is sensitive to the amounts of Clx.

It is recognized that the current 2-D models have several known uncertainties associated with these assessments. For example, in these models the transport of emissions injected near the tropopause is not treated as a resolved meteorological process, but instead as a highly parameterized diffusive process that has not been well tested. We need to develop a good observational database of species that are sensitive measures of cross-tropopause transport including chemically important tracers such as ozone and nitric acid. Furthermore, heterogeneous chemistry and tropospheric chemistry are not well developed and tested in the 2-D stratosphere models.

NEEDS: Basic global assessment models are an important and critical component of the High-Speed Research Program. They must be capable of simulating many possible scenarios for aircraft emissions. These models must have current chemistry and be validated and documented in the scientific literature. The models must be committed to continued improvement and testing; they must be prepared to incorporate basic improvements and new parameterizations of key processes (e.g., stratosphere-troposphere exchange, heterogeneous chemistry, the nonlinear effects of plume chemistry) as the Program develops and uncertainties are reduced. These models must be available to make sensitivity studies for the overall assessment as determined by the HSRP and Advisory Committee.

2. Emissions scenarios

Aircraft are known to emit water vapor, carbon dioxide, carbon monoxide, nitric oxide, sulfur dioxide, unburnt hydrocarbons, soot, trace metals, and condensation nuclei. With the currently available models, the emissions of NO_x in particular are predicted to give some reduction in ozone over much of the stratosphere, with possible enhancements in tropospheric ozone. With current models the impact varies critically with the cruise altitude: the higher the altitude for NO injection (over the altitude range 16-30 km), the greater the predicted ozone loss.

Aircraft emissions in the atmosphere are basically bimodal between the subsonic fleet (<12 km) and the supersonic fleet (>18 km, lower over land if subsonic flight is required). Most emissions from supersonic aircraft are expected at cruise altitude; with higher Mach numbers resulting in higher desired cruise altitudes: e.g., 18 km at Mach 2.4, 23 km at Mach 3.2. It is important to consider as wide a range as possible for the aircraft emissions scenarios, including emission indices and operational range. The NO_x emission index (EI) ranges from 30 to 50 $g(NO_2)/kg(fuel)$ for current combustor technology applied to advanced (i.e., year 2000 and beyond operation) cycle engines for supersonic aircraft. It appears that significant effort would be required to reduce the EI to a range 5-20 (i.e., practical demonstrated limit for stationary turbine applications) in a commercial aircraft engine, and innovative technology is needed for reduction below 5.

NEEDS: This is a critical HSRP element. It is expected that the HSRP, through the related System Studies, will provide the necessary emission scenarios from the aircraft industry. We also will consider independent proposals to augment these basic scenarios.

More detailed emissions scenarios are needed both in terms of clearly defined emission indices (g of chemical substance per kg of fuel) and in terms of operational flight patterns. We need to characterize the emissions of NO_x, H_2O, CO, hydrocarbons, SO_2, condensation nuclei, soot, and metals as a function of aircraft and engines, and also in terms of the conditions under which they are emitted (e.g., altitude, temperature, ascent, or descent). The emission indices must be realistic, including values for today's engines and those projected for future development. The operational flight pattern of emissions must be specified as a function of latitude and longitude as well as time of year. It is important to identify preferential flight corridors. Seasonal effects may be important in determining the effective altitude above the tropopause and the removal of pollutants by the general circulation. Future scenarios should consider emissions from the combined subsonic plus supersonic aircraft fleet as well as the changes in atmospheric composition due to other human activities or climate change.

3. 3-D chemical transport models and longitudinal asymmetry

The initial emissions from aircraft will occur preferentially along flight corridors. Following the initial mixing of the exhaust plumes (see section 4 below), the wind shear should mix the emissions into a zonally uniform distribution in approximately 5 to 20 days. When the identity of the plumes is lost (>20 days), an "intelligently" parameterized zonal-mean 2-D model would be able to correctly calculate the chemical perturbations.

Nevertheless, this time scale for zonal mixing is sufficient to accumulate enhanced levels of emissions within the preferred flight corridors. Chemical eddies (i.e., nonlinear effects in zonal averaging of the chemical terms) are probably of second-order importance after 5-10 days, with the possible exception of heavily travelled flight corridors.

Accurate simulation of the dynamical mixing of tracers in the stratosphere and upper troposphere is also critical for this assessment, since much of the aircraft emissions occur so close to the tropopause. The 3-D models should be used for calculating transport and redistribution of emissions near and above the tropopause because such transport in a 3-D framework is not tuned to an eddy diffusion parameter as for 2-D.

NEEDS: Three-dimensional models are needed in the early stages of this program to evaluate the importance of 3-D processes in mixing the aircraft emissions throughout the atmosphere. (In this role the 3-D CTM's need not include complete stratospheric chemistry.) Specifically, we recognize that the accumulation of effluents in flight corridors and the details of stratospheric removal of NO_x and H_2O (to the troposphere) can be best addressed with the 3-D global CTM's. Further work is needed on the intelligent parameterization of 2-D zonal models (i.e., mean advective circulation plus unresolved, diffusive mixing) that is based on a self- consistent 3-D circulation. Later in this program, it is expected that some 3-D CTM's with full chemistry will be used in the overall assessment (as noted in section 1 above).

4. Plume chemistry and dispersion

Initially, the exhaust plume from an aircraft is hot and highly turbulent; it entrains ambient air, rising and expanding to dimensions of order 100 m. Thereafter, a combination of wind shear and diffusion act to mix the plume with the ambient stratosphere on time scales of a few days or less. Before dispersion the concentrations of NOx and other effluents within the plume are highly concentrated. The chemical system may be driven by nonlinear reactions involving NOx species and by heterogeneous chemistry occurring on aerosol particles. Specific examples of questions to be addressed include: Is there rapid ozone loss inside the plume? Do ice particles grow large enough within the plume to fall out, thereby removing H_2O, HNO_3, HCl, and HBr?

NEEDS: Models are needed to simulate the dispersion and mixing of aircraft engine emissions, on scales from the initial exhaust plume up to the several hundred kilometers as resolved in the global models. During this mixing, the net chemical effects (e.g., perturbations to ozone, transformations of NO_x and chlorine compounds) must be modelled and assessed in so far as they have global impact after mixing with the ambient stratosphere. One goal of this research will be to develop parameterizations of this subgrid process, where necessary, for the global assessment models.

5. Gas-phase and aerosol chemistry

The chemistry of the lower stratosphere is expected to be perturbed in regions where aircraft emissions build up. In this region of the atmosphere, important chemical transformations include gas-phase reactions (especially three-body processes) and heterogeneous chemical reactions on particles (shown to play a major role in perturbing the winter stratosphere at both poles). There are uncertainties in our chemical modeling of the lower stratosphere, even under unperturbed conditions.

Do we understand the chemical cycles in the stratosphere sufficiently well to predict chemical perturbations in the presence of increased concentrations of a wide variety of emissions? For NO_x the chemistry is moderately well understood with the exception of heterogeneous reactions and, possibly, organic nitrates. For H_2O the chemical effects are straightforward, but the impacts on aerosol growth on water vapor at the tropopause are not well understood. The chemistry of CO is understood, and that of CO_2 should have minimal effect. There is a need to define the major hydrocarbon components (CH_4, C_xH_y, C_xC_yO) in aircraft emissions. The natural cycle of SO_2 and sulfates in the stratosphere currently has large uncertainty. Metals are predicted to play a role in the ozone budget of the mesosphere and upper stratosphere through their interaction with HCl and formation of metallic chlorides, but this has not been verified under conditions appropriate to the lower stratosphere.

Further complications to the current chemical models focus on the role of aircraft emissions in heterogeneous processes. If emissions occur in the middle of the natural sulfate aerosol layer, the chemistry in the plume or of the layer itself may be affected by SO_2 emissions. The expected increases in H_2O, HNO_3 and H_2SO_4 may lead to enhanced formation of stratospheric aerosols, including polar stratospheric clouds. Enhanced particle growth and fallout could remove NO_x. We have difficulty modeling gas-particle chemistry now (e.g., the Antarctic ozone hole), and we can expect an enhanced role for aerosol chemistry given the emission of condensation nuclei and other effluents from stratospheric aircraft.

NEEDS: Laboratory measurements and modeling of the chemical processes occurring on aerosols are needed. Many different chemical surfaces may play a role: sulfuric acid, polar stratospheric clouds (type I & II), condensation nuclei from the aircraft. We also need fundamental kinetics measurements, especially for three-body reactions in the lower stratosphere, and for nonlinear reactions important for high concentrations of NO_x, H_2O hydrocarbons and possibly chlorine compounds (e.g., ClO released by aerosol chemistry).

Laboratory measurements and modeling of the microphysics, the growth, and possible fallout of particles will also be important.

6. Tropospheric chemistry

Increased emission of NO_x from the growth of both supersonic and subsonic fleets will likely result in increases in tropospheric NO_x. Enhanced levels of NO_x and nonmethane hydrocarbons are expected to lead to increased levels of ozone under tropospheric conditions, but we cannot currently assess the impacts of the proposed aircraft fleets on tropospheric ozone, and may require 3-D CTM's to do so.

NEEDS: Tropospheric chemistry, especially that involving NO_x, hydrocarbons, and production of O_3, must be developed and included in the global chemical assessment models, especially the 3-D models. A broad database for NO_x and nonmethane hydrocarbons in the upper troposphere should be developed. Current observations need to be gathered and analyzed, and possibly new measurement campaigns designed (see section 8 below).

7. Climate effects

Changes in surface temperature may be driven by radiative forcing due to perturbations in (1) lower stratospheric H_2O, (2) upper tropospheric ozone, or (3) stratospheric aerosols (scattering as well as absorption by soot). The CO_2 emitted by the proposed supersonic fleet is believed to be inconsequential. Further changes in the climate of the middle atmosphere would occur if there were major perturbations to stratospheric ozone, and hence solar heating.

NEEDS: An assessment of the radiative forcing associated with aircraft emissions is a part of this program.

8. Atmospheric observations and field experiments

NEEDS: There is a clear, immediate need for measurements of NO_x, O_3, H_2O and other chemically active species in the lower stratosphere and upper troposphere (see section 6 above) in order to define a reference chemical climatology for this part of the atmosphere. These measurements are a fundamental part of calibrating and testing the global models used in this assessment; they also provide a reference standard for future changes in the chemical composition of the atmosphere.

In the near future there will likely be specific flight campaigns with high-altitude aircraft (probably an ER-2 or similar aircraft) to measure the chemical perturbations and dispersion of aircraft emissions (hopefully from current supersonic aircraft). In this case, we may also consider the feasibility of an atmospheric experiment involving release of an artificial tracer along a flight corridor in the lower stratosphere.

In support of such field experiments, we should begin now to develop the strategy, and hence the instruments, needed to measure the chemical perturbations associated with stratospheric aircraft.

SECTION G

CONTRIBUTORS AND REVIEWERS[*]

Section B
Scientific Assessment of Stratospheric Ozone: 1989 Volume I

CONTRIBUTORS

1. Steering Committee

Co-Chairs

R. T. Watson	NASA Headquarters	USA
D. L. Albritton	NOAA Aeronomy Laboratory	USA

Members

F. Arnold	Max-Planck-Institut für Kernphysik	FRG
R. D. Bojkov	World Meteorolgical Organization	Switzerland
D. Ehhalt	Kernforschungsanlage Julich	FRG
P. Fraser	CSIRO	Australia
I. Isaksen	University of Oslo	Norway
V. Khattatov	State Committee for Hydrometeorology	USSR
C. Mateer	Atmospheric Environment Service (Retired)	Canada
T. Matsuno	University of Tokyo	Japan
M. Prendez	Universidad de Chile	Chile
J. A. Pyle	University of Cambridge	UK
B. H. Subbaraya	Physical Research Laboratory	India
P. Usher	United Nations Environment Programme	Kenya

2. Authors

Chapter 1. Polar Ozone

Coordinator

S. Solomon	NOAA Aeronomy Laboratory	USA

Principal Authors

W. L. Grose	NASA Langley Research Center	USA
R. L. Jones	Meteorological Office	UK
M. P. McCormick	NASA Langely Research Center	USA
M. J. Molina	Massachusetts Institute of Technology	USA
A. O'Neill	Meteorological Office	UK
L. R. Poole	NASA Langley Research Center	USA
K. P. Shine	University of Reading	UK
S. Solomon	NOAA Aeronomy Laboratory	USA

Other Contributors

R. A. Plumb	Massachusetts Institute of Technology	USA

---

[*] Affiliations have been updated to 1990 to give the most current information known.

U. Schmidt	Kernforschungsanlage Julich	FRG
V. Pope	Meteorological Office	UK

Chapter 2. Global Trends

Coordinator

G. Megie	Service d'Aeronomie du CNRS	France

Principal Authors

M.-L. Chanin	Service d'Aeronomie du CNRS	France
D. Ehhalt	Kernforschungsanlage Julich	FRG
P. Fraser	CSIRO	Australia
J. F. Frederick	University of Chicago	USA
J. C. Gille	National Center for Atmospheric Research	USA
M. P. McCormick	NASA Langley Research Center	USA
G. Megie	Service d'Aeronomie du CNRS	France
M. Schoeberl	NASA Goddard Space Flight Center	USA

Other Contributors

L. Bishop	Allied-Signal, Inc.	USA
R. D. Bojkov	World Meteorolgical Organization	Switzerland
W. Chu	NASA Langley Research Center	USA
J. J. DeLuisi	NOAA Air Resources Laboratory	USA
J. F. Frederick	University of Chicago	USA
M. Geller	SUNY, Stony Brook	USA
S. Godin	Service d'Aeronomie du CNRS	France
N. R. P. Harris	University of California, Irvine	USA
W. J. Hill	Allied-Signal, Inc.	USA
R. D. Hudson	NASA Goddard Space Flight Center	USA
J. B. Kerr	Atmospheric Environment Service	Canada
W. D. Komhyr	NOAA Air Resources Laboratory	USA
K. Kunzi	University of Bremen	FRG
K. Labitzke	Freie Universitat, Berlin	FRG
C. Mateer	Atmospheric Environment Service (Retired)	Canada
R. D. McPeters	NASA Goddard Space Flight Center	USA
A. J. Miller	NOAA Climate Analysis Center	USA
R. M. Nagatani	NOAA Climate Analysis Center	USA
G. C. Reinsel	University of Wisconsin, Madison	USA
G. C. Tiao	University of Chicago	USA

Chapter 3. Theoretical Predictions

Coordinator

G. Brasseur	National Center for Atmospheric Research	Belgium

Principal Authors and Contributors

B. A. Boville	National Center for Atmospheric Research	USA
G. Brasseur	National Center for Atmospheric Research	Belgium
C. Bruhl	Max-Planck-Institut für Chemie	FRG
M. Caldwell	Utah State University	USA
P. Connell	Lawrence Livermore National Laboratory	USA
A. De Rudder	Belgium Institute for Space Aeronomy	Belgium

A. Douglass	NASA Goddard Space Flight Center	USA
I. Dyominov	Novosibirk State University	USSR
D. Fisher	E. I. du Pont de Nemours and Co., Inc.	USA
J. F. Frederick	University of Chicago	USA
R. Garcia	National Center for Atmospheric Research	USA
C. Granier	Service d'Aeronomie du CNRS	France
R. Hennig	Max-Planck-Institut für Chemie	FRG
M. Hitchman	University of Wisconsin	USA
I. Isaksen	University of Oslo	Norway
C. Jackman	NASA Goddard Space Flight Center	USA
M. Ko	Atmospheric and Environmental Research, Inc.	USA
S. Madronich	National Center for Atmospheric Research	USA
M. Prather	NASA Goddard Institute for Space Studies	USA
R. Rood	NASA Goddard Space Flight Center	USA
S. Solomon	NOAA Aeronomy Laboratory	USA
F. Stordal	University of Oslo	Norway
T. Sasaki	Meteorological Research Institute	Japan
G. Visconti	University de L'Aquila	Italy
S. Walters	National Center for Atmospheric Research	USA
D. Wuebbles	Lawrence Livermore National Laboratory	USA
A. Zadarozhny	Novosibirk State University	USSR
E. Zhadin	Central Aerological Observatory	USSR

Chapter 4. Ozone Depletion and Halocarbon Global Warming Potentials

Coordinators

R. A. Cox	Natural Environment Research Council	UK
D. Wuebbles	Lawrence Livermore National Laboratory	USA

Principal Authors and Contributors

R. Atkinson	California Statewide Air Pollution Center	USA
P. Connell	Lawrence Livermore National Laboratory	USA
H. P. Dorn	Kernforschungsanlage Julich	FRG
A. De Rudder	Belgium Institute for Space Aeronomy	Belgium
R. G. Derwent	Harwell Laboratory	UK
F. C. Fehsenfeld	NOAA Aeronomy Laboratory	USA
D. Fisher	E. I. du Pont de Nemours and Co., Inc.	USA
I. Isaksen	University of Oslo	Norway
M. Ko	Atmospheric and Environmental Research, Inc.	USA
R. Lesclaux	Universite de Bordeaux	France
S. C. Liu	NOAA Aeronomy Laboratory	USA
S. A. Penkett	University of East Anglia	UK
V. Ramaswamy	NOAA Geophysical Fluid Dynamics Laboratory	USA
J. Rudolph	Kernforschungsanlage Julich	FRG
H. B. Singh	NASA Ames Research Center	USA
W-.C. Wang	Atmospheric and Environmental Research, Inc.	USA

3. Reviewers

Attendees: Review Meeting, 10-14 July 1989, Les Diablerets, Switzerland

D. L. Albritton	NOAA Aeronomy Laboratory	USA
R. D. Bojkov	World Meteorological Organization	Switzerland
G. Brasseur	National Center for Atmospheric Research	USA
D. Cariolle	Meteorologie Nationale EERM/CNRM	France
G. D. Cartwright	NOAA National Weather Service/WMO	USA
M.-L. Chanin	Service d'Aeronomie du CNRS	France
A. Charnikov	Central Aerological Observatory	USSR
R. A. Cox	Natural Environment Research Council	UK
D. H. Ehhalt	Kernforschungsanlage Julich	FRG
J. C. Farman	British Antarctic Survey	UK
D. Fisher	E. I. du Pont de Nemours and Co., Inc.	USA
P. J. Fraser	CSIRO	Australia
J. F. Frederick	University of Chicago	USA
J. C. Gille	National Center for Atmospheric Research	USA
W. J. Hill	Allied-Signal, Inc.	USA
M. Hitchman	University of Wisconsin	USA
A. M. A. Ibrahim	Egyptian Meteorological Authority	Egypt
M. Ilyas	University of Science of Malaysia	Malaysia
J. B. Kerr	Atmospheric Environment Service	Canada
M. J. Kurylo	NASA Hqts/Nat. Instit. Stands. & Technology	USA
C. Mateer	Atmospheric Environment Service (Retired)	Canada
T. Matsuno	University of Tokyo	Japan
M. P. McCormick	NASA Langley Research Center	USA
M. McFarland	E. I. du Pont de Nemours and Co., Inc.	USA
G. Megie	Service d'Aeronomie du CNRS	France
M. J. Molina	Massachusetts Institute of Technology	USA
A. O'Neill	Meteorological Office	UK
A. Owino	Kenya Meteorological Department	Kenya
S. A. Penkett	University of East Anglia	UK
M. J. Prather	NASA Goddard Institute for Space Studies	USA
M. J. Prendez	Universidad de Chile	Chile
J. A. Pyle	University of Cambridge	UK
V. Ramaswamy	NOAA Geophysical Fluid Dynamics Laboratory	USA
J. M. Rodriguez	Atmospheric and Environmental Research, Inc.	USA
J. M. Russell	NASA Langley Research Center	USA
S. Solomon	NOAA Aeronomy Laboratory	USA
R. Stolarski	NASA Goddard Space Flight Center	USA
B. H. Subbaraya	Physical Research Laboratory	India
A. F. Tuck	NOAA Aeronomy Laboratory	USA
P. Usher	United Nations Environment Programme	Kenya
R. T. Watson	NASA Headquarters	USA
D. Wuebbles	Lawrence Livermore National Laboratory	USA

Mail Reviewers

J. G. Anderson	Harvard University	USA
J. K. Angell	NOAA Air Resources Laboratory	USA
R. Atkinson	Bureau of Meteorology	Australia
G. Betteridge	Physics and Engineering Laboratory, DSIR	New Zealand
J. P. Burrows	Max-Planck-Institut für Chemie	FRG

B. Carli	IROF-CNR	Italy
S. Chubachi	Meteorological Research Laboratory	Japan
T. S. Clarkson	Meteorological Service	New Zealand
P. Crutzen	Max-Planck-Institut für Chemie	FRG
D. W. Fahey	NOAA Aeronomy Laboratory	USA
G. Fiocco	University la Sapieuza	Italy
A. Ghazi	Commission of the European Communities	Belgium
L. Gray	Rutherford - Appleton Laboratories	UK
J. S. Hoffman	Environmental Protection Agency	USA
Y. Iwasaka	Nagoya University	Japan
P. Johnson	Physics and Engineering Laboratory, DSIR	New Zealand
P. S. Jovanovic	Association of Scientific Unions	Yugoslavia
J. G. Keys	Physics and Engineering Laboratory, DSIR	New Zealand
V. Kirchoff	INPE	Brazil
D. Kley	Kernforschungsanlage Julich	FRG
Y.-P. Lee	National Tsing Hua University	Taiwan
W. A. Matthews	Physics and Engineering Laboratory, DSIR	New Zealand
R. McKenzie	Physics and Engineering Laboratory, DSIR	New Zealand
A. P. Mitra	Department of Science and Industrial Research	India
J. L. Moyers	National Science Foundation	USA
L. P. Prahm	Danish Meteorological Institute	Denmark
M. H. Proffitt	NOAA Aeronomy Laboratory	USA
L. X. Qui	Academia Sinica	PRC
F. S. Rowland	University of California, Irvine	USA
P. C. Simon	Institut d'Aeronomie Spatiale	Belgium
Y. Sasano	National Institute for Environmental Studies	Japan
J. Swager	Air Directorate	Netherlands
D. W. Wei	Institute of Atmospheric Physics, NEPA	PRC
R. Zellner	University of Hannover	FRG
C. S. Zerefos	University of Thessaloniki	Greece

4. Logistical Support

R. D. Bojkov	World Meteorological Organization	Switzerland
M. -C. Charrierts	World Meteorological Organization	Switzerland
F. M. Ormond	NASA Headquarters/Birch & Davis Associates	USA
J. Waters	NOAA Aeronomy Laboratory	USA

Scientific Assessment of Stratospheric Ozone: 1989
Volume II

EXPERTS AND REVIEWERS INVOLVED IN AFEAS

Experts

R. Atkinson	University of California, Riverside	USA
W. L. Chameides	Georgia Institute of Technology	USA
P. S. Connell	Lawrence Livermore National Laboratory	USA
R. A. Cox	Natural Environment Research Council	UK
R. G. Derwent	Harwell Laboratory	UK
D. L. Filkin	E. I. du Pont de Nemours and Co., Inc.	USA
D. A. Fisher	E. I. du Pont de Nemours and Co., Inc.	USA
J. P. Friend	Drexel University	USA

Contributors

C. H. Hales	E. I. du Pont de Nemours and Co., Inc.	USA
R. F. Hampson	National Institute of Standards and Technology	USA
I. S. A. Isaksen	Oslo University	Norway
L. S. Kaminsky	State University of New York at Albany	USA
M. K. W. Ko	Atmospheric and Environmental Research, Inc.	USA
M. J. Kurylo	National Institute of Standards and Technology	USA
R. Lesclaux	Universite de Bordeaux	France
D. C. McCune	Boyce Thompson Institute for Plant Research	USA
M. O. McLinden	National Institute of Standards and Technology	USA
M. J. Molina	Massachusetts Institute of Technology	USA
H. Niki	York University	Canada
M. J. Prather	NASA Goddard Institute for Space Studies	USA
V. Ramaswamy	Princeton University	USA
S. P. Sander	Jet Propulsion Laboratory	USA
F. Stordal	Oslo University	Norway
N. D. Sze	Atmospheric and Environmental Research, Inc.	USA
A. Volz-Thomas	Kernforschungsanlage, Julich	FRG
W-C Wang	Atmospheric and Environmental Research, Inc.	USA
L. H. Weinstein	Boyce Thompson Institute for Plant Research	USA
P. H. Wine	Georgia Institute of Technology	USA
D. J. Wuebbles	Lawrence Livermore National Laboratory	USA
R. Zellner	University of Hannover	FRG

Reviewers

D. L. Albritton	National Oceanic and Atmospheric Administration	USA
J. G. Anderson	Harvard University	USA
R. E. Banks	Univ. of Manchester Inst. of Science and Tech.	UK
J. J. Bufalini	U.S. Environmental Protection Agency	USA
A. W. Davison	Newcastle University	UK
W. B. DeMore	Jet Propulsion Laboratory	USA
D. D. Des Marteau	Clemson University	USA
R. A. Duce	University of Rhode Island	USA
A. Goldman	University of Denver	USA
M. R. Hoffman	California Institute of Technology	USA
C. J. Howard	National Oceanic and Atmospheric Administration	USA
N. Ishikawa	F&F Research Centre, Tokyo	Japan
J. L. Moyers	National Science Foundation	USA
V. Ramanathan	University of Chicago	USA
A. R. Ravishankara	National Oceanic and Atmospheric Administration	USA
F. S. Rowland	University of California, Irvine	USA
P. Simon	Institut d'Aeronomie Spatiale de Belgique	Belgium
H. O. Spauschus	Georgia Institute of Technology	USA
S. Solomon	National Oceanic and Atmospheric Administration	USA
A. Tuck	National Oceanic and Atmospheric Administration	USA
R. T. Watson	National Aeronautics and Space Administration	USA
S. Wofsy	Harvard University	USA

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LaRoche Chemicals	USA
Montefluos SpA	Italy
Pennwalt Corporation	USA
Racon (Atochem)	USA

Section C

Transient Scenarios for Atmospheric Chlorine and Bromine

M. J. Prather	NASA/Goddard Institute for Space Studies, NY
R. T. Watson	NASA Headquarters, Washington, DC

Section D

Chemical Kinetics and Photochemical Data For Use in Stratospheric Modeling

NASA PANEL FOR DATA EVALUATION

W. B. DeMore, Chairman	Jet Propulsion Laboratory, Pasadena, CA
D. M. Golden	SRI International, Menlo Park, CA
R. F. Hampson	National Institute for Standards and Technology, MD
C. J. Howard	NOAA Environmental Research Laboratory, Boulder, CO
M. J. Kurylo	National Institute for Standards and Technology, MD
M. J. Molina	Massachusetts Institute of Technology, Cambridge, MA
A. R. Ravishankara	NOAA Environmental Research Laboratory, Boulder, CO
S. P. Sander	Jet Propulsion Laboratory, Pasadena, CA

Section E

An Assessment of the Impact on Stratospheric Chemistry and Ozone caused by the Launch of the Space Shuttle and Titan IV

A. R. Douglass	NASA/Goddard Space Flight Center, Greenbelt, MD
M. M. Garcia	NASA/Goddard Institute for Space Studies, NY
C. H. Jackman	NASA/Goddard Space Flight Center, Greenbelt, MD
M. K. W. Ko	Atmospheric and Environmental Research, Inc., Cambridge, MA
M. J. Prather	NASA/Goddard Institute for Space Studies, NY
N. D. Sze	Atmospheric and Environmental Research, Inc., Cambridge, MA

Section F

High-Speed Research Program Atmospheric Advisory Committee

(as of August 1989)

R. J. Cicerone	University of California, Irvine
D. H. Ehhalt	Kernforschungsanlage Julich, FRG
J. R. Holton	University of Washington
H. S. Johnston	University of California, Berkeley
J. G. Lawless*	NASA/Ames Research Center, Moffett Field, CA
J. D. Lawrence*	NASA/Langley Research Center, Hampton, VA
J. D. Mahlman	NOAA/Geophysical Fluid Dynamics Lab, Princeton, NJ
T. Matsuno	Geophys.Inst., Tokyo, Japan
M. J. Molina	Massachusetts Institute of Technology, Cambridge, MA
M. Oppenheimer	Environmental Defense Fund, NY
R. A. Plumb	Massachusetts Institute of Technology, Cambridge, MA
M. J. Prather* (Co-Chair)	NASA/Headquarters, Code SEU, /GISS, NY
A. F. Tuck	NOAA/Aeronomy Lab, Boulder, CO
R. T. Watson* (Co-Chair)	NASA/Headquarters, Code SEU, Washington, DC
H. L. Wesoky*	NASA/Headquarters, Code RJ, Washington, DC
R. E. Whitehead* (Exec. Secretary)	NASA/Headquarters, Code RJ, Washington, DC
L. J. Williams*	NASA Headquarters, Code RJ, Washington, DC
S. C. Wofsy	Harvard University, Cambridge, MA
D. J. Wuebbles	Lawrence Livermore National Laboratory, Livermore, CA

New Members:

E. Condon*	NASA/Ames Research Center, Moffett Field, CA
R. A. Cox	Natural Environment Research Council, UK
W. L. Grose*	NASA/Langley Research Center, Hampton, VA
J. Hoffman*	Environmental Protection Agency, Washington, DC
N. P. Krull*	Federal Aviation Administration, Washington, DC
M. J. Kurylo	NASA/Headquarters, Code SEU, Washington, DC&NIST
R. W. Niedzwiecki*	NASA/Lewis Research Center, Cleveland, OH
A. R. Ravishankara	NOAA/Environmental Research Lab, Boulder, CO

* ex officio

NASA

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R. T. Watson, M. J. Kurylo, M. J. Prather,
and F. M. Ormond

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NASA Office of Space Science and Applications
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16. Abstract

This document is issued in response to the Clean Air Act Amendments of 1977, Public Law 95-95, which mandates that the National Aeronautics and Space Administration (NASA) and other key agencies submit biennial reports to Congress and the Environmental Protection Agency. NASA is charged with the responsibility to report on the state of our knowledge of the Earth's upper atmosphere, particularly the stratosphere. This is the seventh ozone assessment report submitted to Congress and the concerned regulatory agencies. Part I of this report, issued earlier this year, summarized the objectives, status, and accomplishments of the research tasks supported under NASA's Upper Atmosphere Research Program during the last two years.

This report presents new findings since the last report to Congress was issued in 1988. It includes several scientific assessments of our current understanding of the chemical composition and physical structure of the stratosphere, in particular how the abundance and distribution of ozone is predicted to change in the future. These reviews include: (Section B) a summary of the most recent international assessment of stratospheric ozone; (Section C) a study of future chlorine and bromine loading of the atmosphere; (Section D) a review of the photochemical and chemical kinetics data that are used as input parameters for the atmospheric models; (Section E) a new assessment of the impact of Space Shuttle launches on the stratosphere; (Section F) a summary of the environmental issues and needed research to evaluate the impact of the newly re-proposed fleet of stratospheric supersonic civil aircraft; and (Section G) a list of the contributors to this report and the science assessments which have formed our present state of knowledge of the upper atmosphere and ozone depletion.

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SPACE SHUTTLE SAFETY ENHANCEMENTS

October 1990

A Report to

The Committee on Commerce, Science and Transportation
United States Senate

and

The Committee on Space Science and Applications
U.S. House of Representatives

Office of Space Flight
National Aeronautics and Space Administration

In authorizing funding for FY 1990 Shuttle Production and Operational Capability, both H.R. 3729, as passed by the House, and S. 916, as passed by the Senate, directed that NASA undertake a specific series of safety enhancements to the Shuttle orbiter, and that NASA submit a full report to the Congress concerning the status of those enhancements.

NASA is extremely proud of the accomplishments enumerated in this report. The Agency remains committed to the goal of increasing Shuttle safety margins, improving efficiency and reliability, and developing more robust systems. As the following will illustrate, tremendous progress has been made on improvements to the subsystems specified in the Committee Report. These complex and unique systems continue to test the imagination and resourcefulness of our engineers, and this report is a tribute to these qualities as exemplified by the NASA/contractor team. NASA welcomes the Committee's partnership in the pursuit of these important goals.

Space Shuttle Main Engine (SSME)

A program plan has been developed by the SSME project in conjunction with the contractor and government technical experts which addresses the identified limitations of the current engines and is structured to aggressively pursue enhancements for improving the engine. A formal program has been defined which includes enhancements to all items identified in H.R. 1759, and other concerns as well.

* Alternate Turbopump Development:

> This is an alternate high pressure fuel and high pressure oxidizer turbopump design being developed by UTC/Pratt and Whitney which incorporates improved safety margins, reliability, and life, and is being accomplished through a robust approach to the design of the critical features. Over ninety percent of the welds have been eliminated through design changes and utilization of precision castings. The pumps are currently in development testing at Pratt and Whitney, and are scheduled for development testing at Stennis Space Center in December 1990. The pumps are scheduled for incorporation into the fleet beginning in 1993.

* Improved design and installation of High Pressure Oxygen Turbopump bearings:

> Health monitoring instrumentation has been modified to address the condition of oxidizer turbopump bearings after flight, and has been certified and incorporated on the flight pumps. The instrumentation permits two flights without removal, provided the bearing signatures are within acceptable limits. The modification was successfully flown on STS-31. The enhanced Rocketdyne high pressure turbopumps, known as the 10K pumps, were redesigned with the goal of significantly improving the life and reliability of the bearings, and substantially reducing the maintenance requirements and time between overhauls. Currently, the flight turbopumps have to be overhauled every 2,000 seconds. Certification testing, which is still in progress, indicates substantial improvements in life, reliability, maintenance, and overall requirements for the turbine end of the

pump. The modified high pressure fuel turbopump is scheduled for fleet implementation in January 1991, and a modified high pressure oxidizer turbopump configuration is scheduled for fleet implementation in March 1991.

- Installation of the two-duct hot gas manifold:

  The two-duct hot gas manifold, known as the phase II+ powerhead, is an improvement that addresses SSME design margins, reliability, and life-span. The development of the two-duct power head (hot gas manifold) has continued with test results that are frequently better than predicted. Incorporation of this change will alleviate some of the loads internal to the engine; specifically, those resulting from non-uniform velocity and pressure distributions in the flow passages caused by the present three-duct power head. The manufacturing complexity has been improved through the elimination of welds and improved inspection capability, elimination of the preburner injector pins, incorporating the single tube internal heat exchanger (no interpropellant welds) and other design improvements. The first unit has completed 10,000 seconds of development testing at Stennis Space Center, Mississippi. The production of the phase II+ powerhead is currently in progress and scheduled for fleet implementation beginning in 1994.

- Development of enlarged throat diameter:

  The large throat main combustion chamber is an advanced design of the current main combustion chamber that would provide a more benign operating environment for major SSME components. Work on the large-throat main combustion chamber has included testing on the Technology Test Bed and will soon include testing at the Stennis Space Center, Mississippi. Test data show that it can provide major reductions in turbomachinery stress levels and environments. Combustion has been demonstrated to be stable and systems effects that would accompany its incorporation can be accommodated by straightforward modifications to other components, some of which are in work for other reasons. This project is included in a potential SSME advanced fabrication compoment development program that is now under consideration.

- Development of single-crystal turbine blades:

  The single crystal turbine blades were intended to improve the reliability, safety, and life of the Directionally Solidified (DS) blades in the current flight turbopumps. This plan was never implemented because the reliability, safety, and life of the current DS blades were significantly enhanced through improved fabrication techniques and tighter specifications and controls. Single crystal blades are utilized in the Pratt and Whitney alternate turbopumps which are currently undergoing testing and will be incorporated in flight engines in FY 1994.

- General redesign to reduce welds and make welds totally inspectable:

  A single tube heat exchanger, which eliminates many critical welds, will be implemented in FY 1994. In addition, the advanced fabrication components program that is now under consideration would include the redesign of critical components to reduce and/or improve inspectability of welds in the main combustion chamber, nozzle, powerhead and ducts. These improvements would reduce the overall engine cost and further increase reliability, safety, and life of critical components.

Solid Rocket Booster/Solid Rocket Motor

H.R. 3729 and S. 916 also direct "implementation of the recommendations contained in the report of the National Research Council entitled 'Collective Reports of the Panel on Technical Evaluation of NASA's Redesign of the Space Shuttle Solid Rocket Booster', issued in 1988." The recommendations of the National Research Council contained in its report were considered to be a valuable contribution and were carefully reviewed by NASA. A response, and the status of each recommendation, was provided to the Panel Chairman, transmitted by a letter from the NASA Administrator on March 28, 1989. In November 1989, NASA reconvened the Panel to review with its members the program status, and the results of post flight inspection of the redesigned hardware following return to flight.

- Development of a locking feature for the nozzle leak check port plugs:

  Locking features for the various nozzle leak check port plugs were developed, and these features were incorporated into the flight hardware by the sixth RSRM flight (STS-34).

- Development of one-piece case stiffener rings:

  A one-piece case stiffener ring was carried to the point of concept development and analytical evaluation and then discontinued due to findings which indicated the approach was impractical. The purpose of the concept was to eliminate the attrition of case stiffener segments due to cracks occuring at water impact. The attrition rate (approximately 17 percent) is currently being accommodated while the flightworthiness of segments with cracked stubs is being evaluated.

* Development of non-asbestos motor insulation:

Candidate material formulations of a non-asbestos insulation have been selected from three different material suppliers. The three formulations have undergone characterization testing, including sub-scale test firings. Sub-scale test firings will be completed in Fiscal Year 1991, and a selection from these three will be made by September 1991. Development activities have not been approved past that point.

* Enhancement of lightning protection for case and nozzle:

A lightning effects test facility was built at Wendover, Utah and comprehensive tests of lightning discharge effects were conducted on full-scale booster segments. Tests were also conducted at the Corrinne, Utah railhead with segments in the rail transportation configuration. These tests led to development of upgraded bonding adhesives on the Lightning Arresting System tunnel, resulting in improved electrical continuity and greater lightning protection.

* Modification of the aft skirt structure:

Aft skirt structure modification has been under evaluation to obtain an improved structural factor of safety. Redesign of the aft skirt is under consideration for use with the Advanced Solid Rocket Motor (ASRM) Program. Test and evaluation is under way involving a method of installing the RSRM skirt on the mobile launch platform to obtain a favorable pre-load condition which would reduce critical stresses during launch.

External Tank (ET)

* Upgrading of liquid hydrogen and oxygen temperature, pressure, and liquid level sensors:

The majority of the sensor/transducer problems have involved the liquid oxygen and liquid hydrogen pressure transducers. The typical failures have been cases where the transducer exhibited erroneous readings, high contact resistance/signal dropout, or electrical noise. As a result of these production difficulties NASA has qualified new transducers and temperature sensors that eliminate these failure modes. In acceptance test procedures the liquid level sensors have experienced some failures resulting from the production process. Numerous process changes and additional inspections have been implemented to improve sensor quality. The acceptance testing has proven to be an accurate indicator of performance since these sensors have been extremely reliable in flight.

* Upgrading of thermal insulation on areas where dislodged insulation can affect the orbiter:

The application of the intertank thermal protection system (TPS) has been upgraded by the installation and qualification of the new dual spray gun system which applies the TPS in a single layer. The previous method was to apply the TPS in two layers which created a condition where shedding of the outer layer has occurred. TPS closeout procedures at Kennedy Space Center, Florida, have been improved and standardized to simplify processing, reduce rework effort, and also provide a stronger and more reliable insulation. The raw materials used to formulate the TPS are characterized ("finger-printed") upon receipt to ensure that the chemical and physical properties meet the required acceptance criteria.

* Investigation of corrosion prevention methods to preclude structural problems:

The primer developed early in the external tank program provides corrosion inhibition and is undergoing testing and evaluation aimed at extending shelf life certification beyond the present five-year span. This primer meets the dual requirements of providing a substrate for the TPS and protection from corrosion.

Orbiter

* Modification of structure to eliminate negative margins:

Analysis indicates that the great majority of the orbiter structure has positive safety margins. Constraints have been defined for critical structures (wings, tail, aft fuselage, OMS pods, and wing leading edges) to ensure positive safety margins. Since launch probability can degrade due to constrained structure, structual modifications are being made as program requirements dictate. Analysis is founded on the Design Certification Review of March 1988, when the allowable flight envelope was revised according to certification derived from the 6.0 loads/stress analysis. The scope of the analysis used in certification included 60,000 structural components and 30 major structural elements including the wing, vertical tail, and mid-fuselage.

During their respective major modification/structural inspection periods in FY 1991 and FY 1992, OVs 102, 103, and 104 will receive modification installations of aft fuselage OMS deck frames, wing truss tubes, wing upper skin panels, and wing spar webs and joints. Installation of these modifications will complete the practical and cost-effective improvements to eliminate orbiter structural limitations to operating envelope and maximize launch probability.

- Upgrading of the auxiliary power units:

  Goals of the Improved APU program are to improve reliability and valve seat material, extend system life and component life, eliminate refurbishment and reduce turnaround costs, eliminate water valve corrosion, and reduce weight. The improvement program will eliminate the APU as a Criticality 1 failure item, extend system life to 75 hours, eliminate voids in the catalyst bed, eliminate turbine housing cracks, provide dual fuel pump seal drains, and preclude turbine wheel blade cracking.

  Improved APUs were installed in OV-105 this summer, and are scheduled for installation in OV-102 by the fourth quarter of FY 1991. First flight of the improved units is to be in March 1992 aboard OV-105 on STS-49.

  A program is also underway to deliver an improved APU controller to overcome design obsolescence (digital v. analog), improve reliability, and reduce the frequency of repairs. Critical Design Review is scheduled for October 1990 with qualification testing extending through May 1991. Delivery of the first three flight units is projected by July 1991 with first flight aboard OV-105 on STS-49, scheduled for March 1992.

- Development of a redundant nose wheel steering system (including possible extension of the nose wheel strut):

  The redundant nose wheel steering system underwent a Preliminary Design Review October 1988 and Critical Design Review in February 1989. The system will eliminate single-point avionics failures. Completion of qualification of the system and first delivery are scheduled for December 1990. First flight is scheduled on STS-43.

  Preliminary Design Review of a second hydraulic supply was completed in May 1989 and Critical Design Review in July 1989. Qualification and delivery are scheduled for November 1990, with first flight planned for STS-49 in March 1992.

  A study was conducted to investigate the use of an articulated nose wheel strut. It was determined that only a small improvement in landing gear loads could be realized and that the cost required for minimal benefit was not warranted.

- Elimination of Kapton electrical wire insulation:

  The program does not plan to eliminate Kapton-insulated wiring because no better insulation is currently available. Instead, our plan is to install protection in the form of convoluted tubing, which would prevent damage that might result in either arc tracking or flashover. In June 1990 the Level I Program Requirements Control Board (PRCB) directed inquiry to accomplish the following:

- Perform an assessment of high traffic areas in the orbiter where Kapton insulated wire damage can occur during turnaround processing, and identify wire protection installation based on the launch site flow review.

- Evaluate configuration status accounting for each orbiter to ensure that installation of convoluted tubing is accurately documented to assure similar installation in OV-105.

- Evaluate the benefits of opening both orbiter aft access doors during turnaround processing in order to reduce inadvertent Kapton wire damage in the aft compartment.

- Devise a plan identifying cost and schedule impacts of performing a Failure Mode Effects Analysis identifying the criticality of all orbiter wire bundles.

A Level II PRCB review of the results of this inquiry is scheduled for October 25, 1990. Results of Kapton wire testing at Johnson Space Center, Texas, will be reviewed by the Level II PRCB in November. Level I PRCB review of these findings will be conducted.

* Upgrading of valves and regulators to preclude leakage of fuels and oxidizers:

A 14-inch design of the Orbiter/ET umbilical is in work to replace the existing 17-inch design. The redesign features fewer moving parts and totally eliminates moving parts in the propellant flow stream, as well as provide reduced penetrations to leak, lower pressure drop, and redundant seals. The first flight is scheduled aboard OV-105 in April 1993, with fleet change to be accomplished during orbiter modification periods.

A new fixed orifice design for liquid oxygen flow control valves will have no moving parts to improve reliability and eliminate failure modes. The redesign will be tested on the upcoming STS-41 mission, and will be incorporated into the fleet during 1991-92.

A new bellows design will improve stability and eliminate fatigue concerns in the helium 750 PSI regulator. The new design will be delivered in November 1990 with first flight in 1992 and fleet changeover in 1992-93.

Helium check valves are being redesigned to eliminate a jamming problem with the current design. The new design is now available and it is being installed on an attrition basis.

THE SECRETARY OF COMMERCE
Washington, D.C. 20230

ROE

October 31, 1990

Honorable Robert A. Roe
Chairman, Committee on Science,
  Space, and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

I am pleased to submit the report, "Network for the Detection of Stratospheric Change: A Status and Implementation Report," in compliance with Section 410 of the National Aeronautics and Space Administration Authorization Act (P.L. 100-685).

This document was jointly prepared by the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration. It is based on the results of an international planning meeting on the Network for the Detection of Stratospheric Change.

Sincerely,

Robert A. Mosbacher

Enclosure

NETWORK FOR THE DETECTION OF STRATOSPHERIC CHANGE

A STATUS AND IMPLEMENTATION REPORT

January 1990

516

Issued by:

NASA Upper Atmosphere Research Program and NOAA Climate and Global Change Program

Prepared by:

M. J. Kurylo, NASA Headquarters, Washington, DC
(Interagency assignment from NIST, Gaithersburg, MD)

and

S. Solomon, NOAA Aeronomy Laboratory, Boulder, CO

Copies available from:

Code EEU
NASA Headquarters
600 Independence Ave, S. W.
Washington, DC 20546

and

NOAA Aeronomy Laboratory
R/E/AL8
325 S. Broadway
Boulder, CO 80303

FOREWORD

The National Oceanic and Atmospheric Administration, in association with the National Aeronautics and Space Administration, was tasked with preparing "a plan to construct and operate a worldwide system of ground-based remote sensors to monitor the stratospheric levels of chemicals which can affect the level of ozone in the stratosphere and to use these results to improve our understanding of the possible changes in stratospheric ozone that are the consequence of human activities" by the U.S. Senate Committee on Commerce, Science, and Transportation and the U.S House of Representatives Committee on Science, Space, and Technology in Public Law 100-685, the NASA Authorization Act. This document contains the current status and implementation report of the Network for the Detection of Stratospheric Change, based on an international organizational meeting held in November, 1989.

U.S. DEPARTMENT OF COMMERCE

Robert A. Mosbacher, Secretary

John A. Knauss, Undersecretary for Oceans and Atmopshere

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SUMMARY

Network for the Detection of Stratospheric Change (NDSC)

The Network for the Detection for Stratospheric Change is a set of high-quality remote-sounding research stations for observing and understanding the physical and chemical state of the stratosphere, complimented by secondary stations and satellite measurements. Ozone and key ozone-related chemical compounds and parameters are targeted for measurement. This document is a summary of the current status of the network and is based largely on the results of an international organizational meeting held in Geneva, Switzerland during November, 1989. The document includes a detailed description of the background of the NDSC, its instrumentation, scientific goals, site considerations and management.

Goals of the Network

- To make the observations through which changes in the physical and chemical state of the stratosphere can be determined and understood. In particular, to make the earliest possible identification of changes in the ozone layer and to discern the cause of the changes.
- To provide an independent calibration of satellite sensors of the atmosphere.
- To obtain the data that can be used to test and improve multi-dimensional stratospheric chemical and dynamical models.

Instruments

The primary NDSC instruments were selected based on their ability to satisfy the measurement priorities discussed in Section 1.1 of this report. The anticipated primary instruments and measurements are:

- Ozone lidar (vertical profiles of ozone from the tropopause to at least 40 km altitude; in some cases tropospheric ozone will also be measured)
- Temperature lidar (vertical profiles of temperature from about 30 to 80 km)
- Aerosol lidar (vertical profiles of aerosol optical depth in the lower stratosphere)
- Ozone microwave (vertical profiles of stratospheric ozone from about 20 to 70 km)
- H_2O microwave (vertical profiles of water vapor from about 20 to 80 km)
- ClO microwave (vertical profiles of ClO from about 25 to 45 km, depending on latitude)
- Ultraviolet/Visible spectrograph (column abundances of ozone, NO_2, and, at some latitudes, OClO and BrO)

- Fourier Transform Infrared spectrometer (column abundances of a broad range of species including ozone, HCl, NO, NO_2, $ClONO_2$ and HNO_3)

Brief descriptions of each instrument are provided in the instrument summaries (Sections 2.1 through 2.4). Further details may be found in the references.

Sites

Depending on specific site characteristics (i.e., geography and meteorology), each primary NDSC station will be equipped with most of the above instruments and may also have some additional ancillary measurement capabilities. Important scientific information may also be collected at other sites with partial instrument complements. Two initial primary sites have been selected, one other primary candidate has been identified, and several others are under consideration. Ultimately, primary sites are planned for at least six locations: high latitudes in the northern hemisphere (to be determined), mid-latitudes in the northern hemisphere (made up of several Alpine locations including Haute Provence, France and the Jungfraujoch, Switzerland), subtropics in the northern hemisphere (Mauna Loa, Hawaii, USA), tropics (to be determined), midlatitudes in the southern hemisphere (possibly Lauder, New Zealand), and high latitudes in the southern hemisphere (in Antarctica).

Organization and Data Protocol

The organization of the NDSC consists of a Steering Committee and a Science Team. The Steering Committee is the primary managerial body of the NDSC. As a representative group, it has the responsibility for such NDSC activities as internal operational oversight, scientific oversight, and recommending implementation and funding actions. The larger Science Team consists of all of the Principal Investigators (PIs) associated with each of the instrument types.

The Network's data lie at the heart of its contribution to understanding stratospheric change. As with any good research, the PIs bear the responsibility for its quality. The use of the data will follow a protocol, the proposed main features of which include:

- an initial one-year period during which PIs analyze, develop and publish their own data or release it to other researchers of their choice,

- a two-year period during which any of the NDSC PIs can use the data,

and finally,

- subsequent availability to the international scientific community.

NDSC: Science

1. Introduction

In this report, the current state of science relevant to the NDSC will be summarized. The history of the NDSC will be reviewed, with particular emphasis on its inception, which was formalized largely through a meeting in Boulder, Colorado in 1986 (Section 1.1). In Section 1.2, subsequent scientific developments from 1986 through 1989 will be briefly described, with particular emphasis on the rapid growth in ground-based measurements that resulted in large part from studies in Antarctica during 1986 and 1987. The detailed scientific summary of the November, 1989 Geneva meeting, at which the managerial and operational organization of the NDSC was formalized, is the subject of Sections 2, 3, and 4. In Section 2, the instruments identified for the network will be described, including their estimated accuracies and capabilities, and site requirements. Section 2 also includes a summary of the results of a recent ozone intercomparison campaign that took place at Table Mountain Facility (TMF), involving most of the NDSC ozone measuring instruments. Section 3 presents considerations relevant to site selection considered at the Geneva meeting, along with up-to-date projections from a photochemical model regarding possible trends in chemical species observable by NDSC instruments. Section 4 describes the progress made in plans for data archiving. The current management considerations including the data protocol and the organizational structure, are presented in the NDSC management section of the report.

1.1 The Inception of the NDSC

A broad research program to understand the physics and chemistry of the Earth's upper atmosphere and its susceptibility to change due to natural and anthropogenic effects has been in place since about the mid-1970's. This combined program under the auspices of the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA) and the Chemical Manufactureres' Association (CMA) supported a wide range of investigations including field measurements (utilizing ground, aircraft, balloon, rocket, shuttle and satellite platforms), laboratory kinetics and spectroscopy, modeling and data analysis. The major results and understanding obtained from this decade-long effort were summarized in the recent assessment report issued by *NASA* [1986] and by a large international panel organized under the auspices of the World Meteorlogical Organization [*WMO*, 1990].

Total ozone has been measured at a few dozen stations worldwide approximately since the International Geophysical Year (IGY) in 1957. The importance of such long-term measurements was dramatically illustrated through the discovery of the Antarctic ozone hole by scientists from the British Antarctic Survey [*Farman et al.*, 1985] based on three decades of total ozone measurements at Halley Bay, Antarctica. Due to the paucity of ancillary measurements (e.g., observations of chemical constituents within the NO_x and ClO_x families and accurate temperature data), the cause of the Antarctic ozone hole could not be immediately identified following its discovery [see the review by *Solomon*, 1988]. Several candidate theories emerged, and discrimination between them required field campaigns aimed at measuring not just ozone alone, but also a broad range of the chemical species and physical parameters that can influence stratospheric ozone.

The observation of Antarctic ozone depletion, as well as considerable advances in the technology required to measure other stratospheric species from the ground, suggested that the time to consider assembling a more detailed stratospheric monitoring program was at hand. Indeed, the notion of a ground-based long term measuring network specifically designed to provide the earliest possible detection of changes in the composition and structure of the stratosphere and, more importantly, the means to understand the causes of those changes began to assume both increased urgency and increased practicality. In order to evaluate the feasibility of measuring such changes and identifying their causes, a workshop was held in Boulder, Colorado, on March 5-7, 1986, jointly sponsored by NASA, NOAA and CMA. This meeting brought together chemical and dynamical modelers and experimenters with the specific goals of:

1. Identifying and prioritizing the key atmospheric parameters that must be monitored in order to observe important changes in the structure of the atmosphere.

2. Discussing the magnitudes of possible trends in these key species, and thereby determining the accuracy, precision, vertical resolution and frequency of measurements required to detect these trends

3. Determining the number and locations of stations required to establish a useful network

4. Evaluating currently available measurement techniques to determine their capability to satisfy the requirements, and identify new instrumentation required.

Assumptions

There are several key assumptions inherent in the choice of instrumentation and approach for the network, including:

1. Existing and planned satellite measurement activities will continue, e.g. SBUV measurements on the NOAA operational satellites.

2. The Atmospheric Lifetime Experiment/Global Aerosols and Gases Experiment (ALE/GAGE) and NOAA Global Monitoring for Climatic Change (GMCC) networks are satisfactory for monitoring at ground level long-lived gases such as $CFCl_3$, CF_2Cl_2, CCl_4, CH_3CCl_3, N_2O, CH_4 and CO_2.

3. Total column ozone measurements by the Dobson network provide the longest available record of stratospheric composition. Intercomparison of the Dobson network to the NDSC and satellite instruments is a critical component in attempts to characterize ozone trends worldwide.

4. Current temperature measurement systems are inadequate for the accurate determination of long-term stratospheric temperature trends.

5. Virtually all other species have no systematic long term measurements.

Objectives of the Network

Long Term: The major goal of the network is a long-term one; viz.,

- to provide the earliest possible detection of changes in the stratosphere, and the means to understand them.

Short Term: Although the proposed network is intended for long-term trend detection, it will provide extremely valuable scientific returns in the near term as well, including:

- studying the temporal (diurnal, monthly, seasonal and annual) and spatial (latitudinal) variability of atmospheric composition and structure. Such measurements will provide detailed understanding of the partitioning within the key chemical families.
- providing the basis for ground truth and complementary measurements for satellite systems such as the NASA Upper Atmosphere Research Satellite (UARS), scheduled for launch in the fall of 1991, as well as the Total Ozone Mapping Spectrometer (TOMS) and the Solar Backscatter Ultra-Violet (SBUV) ozone monitoring instruments.
- critically testing multi-dimensional stratospheric models and providing the broad data base required for improved model development.

Priorities

The 1986 workshop identified the following measurements as being of the highest priority to such a network:

1. Column ozone
2. Vertical profile of ozone (0-70 km)
3. Temperature (0-70 km)
4. Vertical profile of ClO
5. Vertical profile H_2O
6. Vertical distribution of aerosols
7. Vertical profile or column of NO_2
8. Stratospheric column of HCl
9. Vertical profiles of long-lived tracers: CH_4 and N_2O
10. Other species (HNO_3, OH, and $ClONO_2$)

Some of the considerations that led to the above list are:

1. Column ozone controls the penetration of solar ultraviolet radiation to the Earth's surface. Changes in column ozone may have possible consequences for human health and terrestrial and oceanic ecosystems.

2. The vertical distribution of ozone controls the temperature structure and hence plays an important role in the circulation of the stratosphere. Changes in the vertical distribution of ozone can influence the climate of the Earth's stratosphere.

3. The temperature of the stratosphere controls the rates of chemical reactions. Thus, it governs the catalytic efficiencies of the different chemical families in controlling the abundance of ozone. In addition, the temperature structure of the stratosphere itself is controlled by the ozone distribution.

4. The ClO radical is the chlorine species responsible for directly catalyzing the destruction of ozone. Its atmospheric concentration was predicted to be increasing at a rate of at least 5% per year in 1986 due to the increasing atmospheric concentrations of chlorofluorocarbons.

5. Water vapor plays a vital role in controlling the radiative and chemical balance of the stratosphere. It is the dominant source for the hydroxyl radical, which controls the catalytic efficiencies of the HO_x, NO_x and ClO_x families towards ozone. The concentration of stratospheric water vapor is expected to increase due to increasing concentrations of atmospheric methane, and may alter if the Earth's climate becomes warmer and affects the exchange of water across the tropopause.

6. While aerosols are not thought to play a major role in the chemistry of the unperturbed stratosphere, they may become important both chemically and radiatively, following major volcanic eruptions, and in the Antarctic. In addition, the presence of high levels of aerosols can influence the interpretation of some optical sensor data.

7. NO_2 is the nitrogen species directly responsible for the catalytic control of ozone and, along with NO, plays a vital role in coupling the NO_x and ClO_x families. Consequently, the atmospheric concentration of NO_2 may decrease in the future because the predicted increased concentrations of ClO will convert it into $ClONO_2$. Conversely, increases in the concentration of N_2O (the stratospheric source of NO_x) will offset some of these decreases.

8. HCl is the key temporary reservoir species in the ClO_x family. It should be monitored in conjunction with ClO in order to see whether the partitioning of species within the chlorine family is changing with time.

9. CH_4 and N_2O are the gases with long stratospheric lifetimes and quite simple photochemical removal mechanisms: photolysis for N_2O, and reaction with OH for CH_4. This makes them ideal tracers for studying changes in atmospheric circulation.

10. Measurements of several other chemical species would also provide important information on changes in the composition of the stratosphere. These include $ClONO_2$, HNO_3, OH, HO_2NO_2 and H_2O_2. Measurements of these species were thought to be of a lower priority at the time of the 1986 evaluation.

Instrumentation

In order to evaluate the suitability of existing measurement systems to make the requisite measurements, review talks were presented by experimentalists having a great deal of expertise with each instrumental technique, although generally not experienced in using that instrument in a long-term observing mode. Based on the discussions generated by those talks, the following overlap of species and ground-based techniques emerged:

Species	Instrument	Status in 1986*	Status in 1989*
O_3 column	Dobson	operating	operating
O_3 (0-20 km)	YAG lidar	under development ready 1 year	operating
(15-45 km)	excimer lidar	under development, ready 1 year	operating
(25-75 km)	microwave	ready to proceed	operating
Temperature	lidar	demonstrated	operating
ClO (25-45 km)	microwave	demonstrated	under development
H_2O (0-30 km)	balloon hygrom.	operating	operating
	microwave	proposed (>35km), demonstrated (>45 km)	under development (>35 km) under development (>20 km)
aerosols (0-30 km)	lidar	demonstrated	under development
NO_2 strat col	UV/Vis spectr.	demonstrated	operating
HCl strat col	IR	demonstrated	operating
CH_4 strat col	IR	proposed	operating
N_2O (20-50 km)	microwave	proposed	demonstrated
HNO_3 strat col	IR	proposed	operating
$ClONO_2$ str col	IR	proposed	demonstrated
OH (40-60 km)	UV fluorescence	proposed, research mode	research mode
	excimer lidar	proposed, minimum 3-year to feasibility	research mode
HO_2 (30-60 km)	microwave	demonstrated	demonstrated

*Definitions:

Operating--currently being used in a routine observing mode; in the case of H_2O, the frost point hygrometers are launched at the rate of 1 per month at 1 station--expansion is necessary.

Demonstrated--the technique has been used in a research mode to measure the particular species; work is required to make the technique network-operational.

Under development--NDSC class instruments are being developed.

Proposed--the technique is believed to be technically sound, but the particular measurements have not been made.

Research Mode--Preliminary studies have been carried out, but the technique is a subject of additional laboratory and field research.

Station Considerations

For nearly all of the instruments, it is desirable to locate the monitoring station at high elevation (>2000 meters) in order to minimize the tropospheric water and aerosol columns. Since the goal of the network is to detect small, long-term trends, it will be necessary to conduct measurements on virtually a daily basis for some applications. This precludes the concept of timesharing, e.g., using a single microwave instrument to monitor both ozone and ClO. Except for the IR and UV/Vis instruments (which obtain data for all species simultaneously), all other instruments will be dedicated to a particular species measurement. This will allow the buildup of a large, continuous database, which is essential for trend detection. The goal of understanding the cause of changes, rather than just detecting them, requires that the instruments be co-located, to an extent consistent with the temporal/spatial requirements of the measurements and the realities of site availability. A closely coupled effort in theory and modeling is also necessary for interpreting the measurements.

Network and Implementation

Since the purpose of this network is to provide early identification of stratospheric change, it is prudent to locate the stations with as much latitude coverage as possible, given the obvious constraints of funds and resources. Therefore, an optimal network would require 5 or more stations: mid-latitude and polar in both hemispheres as well as a tropical station. At the 1986 meeting it was felt that the network might begin with funding from NASA, NOAA and CMA. However, a fully implemented network will require international collaboration both scientifically and managerially, with numerous national cosponsors, complemented by WMO and United Nations Environmental Program (UNEP) monitoring activities. In particular, it should be noted that pre-eminent monitoring research is already underway at the Observatoire de Haute Provence (OHP) in France and the Jungfraujoch Observatory in Switzerland.

In North America, major development efforts for ozone lidar systems were underway in 1986 at Goddard Space Flight Center (NASA/GSFC) (a mobile stratospheric lidar), NOAA's Fritz Peak Observatory (a tropospheric/lower-stratospheric lidar), and the Jet Propulsion Laboratory's (JPL) Table Mountain Facility, TMF (tropospheric and stratospheric lidars). At the time of the 1986 meeting, it was suggested that the TMF site could possibly serve as one of the first network stations and would likely be used as a research site, with new instruments first being installed and tested at TMF before proceeding with full scale deployment. It was recognized that the stations would likely be based at existing, observatory-type sites where many of the required facilities may already exist. The near-term goal set in 1986 was to develop two stations within the first 2-3 years and expand to 5-6 stations within 5 years.

In order for this long term effort to be successful, there are several issues that must be addressed with regard to management, personnel and quality control. It is essential that the design phase for the network involve experimentalists, theorists, data analysts, and statisticians to address the issues of measurement frequency, accuracy and precision. Quality control must be achieved through rigorous calibration procedures and intercomparisons. The success of the ALE/GAGE network demonstrates that this is achievable in practice. It will be a difficult undertaking for traditional research groups to dedicate themselves to the sort of routine, systematic measurements that are required for trend detection, especially since there will be multiple sites involved. While skilled local talent may be used for much of the day-to-day data taking, it will be essential to have senior PIs actively involved in the measurements, at a minimum through site visits/calibrations and data analysis/checking at the home institution.

Lastly, the supporting organizations and agencies must recognize that the project is a long-term commitment.

Costs

It was very roughly estimated that capital costs would be about $2-3 million per station for the instruments described earlier. Operating costs for the full 5 station network are likely to be in the $1-2 million/year range. These costs are substantial. This long term measurement program will represent a major component of the existing international upper atmosphere research effort.

Conclusions of the 1986 meeting

It is clearly valuable to develop a systematic measurements program in order to provide an early detection of stratospheric changes and an understanding of the processes and perturbations causing those changes. The instrumentation and technology to accomplish the measurements are available. Although there are new difficulties in terms of management and quality control, they are not insurmountable. The costs of this program are high and can only be met through cooperation among the interested agencies and organizations, all of whom will be required to affect a significant redirection of their resources. The global aspect of the NDSC coupled with the level of resources required (economic and scientific) emphasizes the need of its international scope.

1.2. Subsequent Major Scientific Developments Relevant to the NDSC (1986 through 1989)

During the 1986 NDSC meeting, it became clear that many of the instruments needed for ground-based measurements of stratospheric ozone and the processes that influence it were already available. This led to the organization of a ground-based expedition to Antarctica to investigate the ozone hole during August to November, 1986. This and the second ground-based expedition in 1987 involved many of the instruments suggested for the network including: microwave ozone, ClO, and N_2O measurements, FTIR total column measurements, UV/Vis spectrographs for NO_2 and O_3, and aerosol lidar. In addition, balloonsonde measurements of ozone, aerosol and temperature were also carried out. It was shown that the UV/Vis technique could also provide measurements of OClO and BrO under the chemically perturbed conditions of the Antarctic ozone hole [*Solomon et al.*, 1987*b*; *Carroll et al.*, 1989]. Observations of stratospheric aerosols by the lidar and balloonsondes illustrated the persistence of polar stratospheric clouds, and the ozone profiles showed that the bulk of the Antarctic ozone depletion was confined to the region from about 10 to 22 km [*Hofmann et al.*, 1987]. The millimeter wave technique was also applied to observations of stratospheric N_2O [*Parrish et al.*, 1988*a*] and HCN [*Jaramillo et al.*, 1989], which are two important dynamical tracers. The suite of measurements taken together provided evidence for substantial chemical perturbations to the composition of the Antarctic spring stratosphere, including greatly elevated lower stratospheric ClO [*de Zafra et al.*, 1987] and OClO abundances accompanied by reductions in NO_2 and HCl [and, in particular, the HCl/HF ratio; see *Farmer et al.*, 1987]. The picture that emerged from the analysis of these observations pointed strongly towards halogen chemistry as the most likely cause of the ozone hole.

The expeditions firmly established the operational performance of typical NDSC instruments. They also underscored the importance of such measurements in future attempts to detect and understand trends in stratospheric composition.

The observation of polar ozone depletion spurred a great deal of other research worldwide regarding ground-based measurements. A complete review is beyond the scope of this brief report. However, a few important examples include: (i) lidar systems were operated during winter at the South Pole, providing the first systematic winter measurements of aerosols there [*Fiocco et al.*, 1989] and (ii) ground-based visible spectroscopy instruments were operated in the Arctic by French [*Pommereau and Goutail*, 1988*a*] and U. S. investigators [*Solomon et al.*, 1988] to search for perturbations in OClO and NO_2 there, in like manner to the Antarctic studies.

Considerable progress was also made for measurements at sub-polar latitudes. An eight-year record of daily measurements of the column abundance of stratospheric NO_2 was reported from New Zealand [*Johnston and McKenzie*, 1989]. Observations of temperature trends based on lidar measurements were reported by *Chanin et al.* [1987]. Systematic observations of mesospheric water vapor were carried out using the millimeter wave technique [*Bevilacqua et al.*, 1989]. By the end of 1989, the technology, scientific interest, and breadth of ground-based studies was rapidly advancing.

The International Ozone Trends Panel (IOTP) report released in 1988 revealed for the first time strong evidence for significant downward trends in total ozone over regions other than Antarctica. This international study was the result of an intensive effort involving over a hundred scientists, in which the ground-based and satellite ozone observations were examined in detail. Long-term trends in total ozone from 1969 to 1986 as large as 5-8% were identified in the Arctic winter, while trends ranging from 1.7 to 3% were found between 30 and 64° in the Northern Hemisphere. A full description of this study is provided in *IOTP* [1990].

The IOTP report underscored the need for the NDSC and enhanced its urgency in at least three important ways:

1) The IOTP report confirmed that total ozone trends are not confined to Antarctica. Further, as in the initial stages of discovery of the Antarctic ozone losses, these trends could not be unambiguously assigned to the effects of chlorofluorocarbons based on available data. Unlike the Antarctic ozone hole, the origin of such trends cannot be understood from a limited series of "campaign-style" measurements, but require a systematic, long-term program of measurements of a broad range of stratospheric species and dynamical tracers.

2) The IOTP report demonstrated that satellite measurements alone are not adequate to determine global trends. While satellites provide indispensable global coverage, they furnish generally limited information about long-term trends because of the difficulty of maintaining long-term calibrations standards in space. The elucidation of global trends in the IOTP report was made possible through detailed examination of ground-based data in concert with satellite measurements.

3) The IOTP report suggested that local ozone near 40 km had declined by 3% over the period from about 1980 to 1986 based on satellite observations by the Stratospheric Aerosols and Gases Experiment (SAGE I and II). A concommittant decline in temperature of 1.7°K was also reported. The observed temperature and ozone decreases were consistent with those predicted from theoretical models including the effects of chlorofluorocarbons and the solar cycle. More definitive study requires both a longer time series and observations of other chemical species including ClO.

2. Description of NDSC Instruments and Intercomparisons

Each of the instruments planned for the network will be briefly reviewed in this section. References will be provided to more extensive discussions of the instrumental techniques, accuracies and error analyses. Where possible, particular groups involved in current measurements and their activities in connection with the network will be described.

The results of the first ozone intercomparison involving NDSC instruments will be briefly summarized in Section 2.5.

2.1. Light Detection And Ranging (LIDAR)

The laser radar method is the only stratospheric remote sensing technique capable of providing high resolution (order of 100-300 m) vertical profile measurements. The technique involves emission of powerful laser light, a small fraction of which returns to the detector because of atmospheric backscatter. Since the speed of light is well known, the altitude of backscatter is determined by the time delay between laser emission and detection.

Lidar measurements of ozone are based on the differential absorption lidar (DIAL) technique [c.f., *Megie and Menzies*, 1980] which requires the simultaneous emission of two laser wavelengths, one of which is much more strongly absorbed by ozone than the other. Typically XeCl excimer laser light at 308 nm and Nd-Yag laser light at 335 nm are used. The backscattered signals are collected by a telescope and detected by two photomultiplier tubes. This technique requires essentially clear sky, since the presence of clouds reduces the signal received from high altitudes. Details of the experimental procedure are presented in *Pelon and Megie* [1981, 1982]. Measurement of the ozone vertical distribution from 18-45 km typically requires a 3-hour integration time for nighttime measurements. Two types of error can influence the DIAL measurement of the ozone vertical distribution: the statistical error related to the signal-to-noise ratio defines the limits on the precision of the measurement, while the systematic error due to molecular and aerosol scattering, extinction by other absorbers and temperature dependence of the ozone absorption cross sections defines the absolute accuracy. The random error for measurements below about 40 km is less than 3%, while the absolute accuracy is better than 10%.

Measurements of the backscattered radiation at 532 nm (Nd-YAG laser light) have long been used to deduce information on aerosols and temperature. The amplitude of the backscattered radiation is related to Rayleigh scattering by atmospheric molecules and any backscatter by particles. Where particles are present, the lidar signal provides the scattering [illegible], which characterizes the aerosol contribution to atmospheric scattering. The scattering ratio is measured from 9 to 28 km with current systems, with an overall accuracy of about 10%. An important parameter used to determine the scattering ratio is the phase function (ratio of the aerosol backscattering to extinction coefficient), which depends on the optical properties of the aerosols. Above about 30 km, where the aerosol scattering becomes small, measurements of the scattering intensity are proportional to the atmospheric density and hence to the atmospheric scale height, from which temperature can be deduced.

There are several research groups involved in NDSC lidar measurements. The group at the Centre National de Recherche Scientifique (CNRS) has a long-standing program in lidar ozone, temperature and aerosol measurements at Biscarosse and Haute Provence (Megie and co-workers). JPL has constructed a stratospheric ozone lidar and is presently involved in constructing a tropospheric system (McDermid and co-workers). A mobile stratospheric ozone and temperature lidar has been constructed at NASA's Goddard Space Flight Center (McGee and co-workers). In addition, the NOAA Aeronomy Laboratory is involved in construction of a tropospheric ozone lidar at its observatory near Boulder, Colorado (Proffitt and co-workers). The group from the University of Rome (Fiocco and co-workers) has carried out measurements of stratospheric ozone, temperature and aerosols at a wide variety of sites including the South Pole, while the Japanese group has a similar system at Tsukuba (Uchino and co-workers). Finally, scientists in Canada and Holland are also building ozone lidar systems.

The technique as envisioned for the network will yield the following measurements:

Quantity	Height Range	Vertical resolution	Accuracy
Ozone density	20-35 km	200 m	<3%
	35-50 km	200 m	~10%
Temperature	30-70 km	200 m	<2K
Aerosols	9-26 km	200 m	10%

Site Requirements The ozone lidar is severely affected by clouds. Operation with thin cirrus clouds is possible, but the signal is significantly reduced with all the corresponding reductions in precision, altitude range, etc. Clear skies are required. Coastal regions with high incidence of fog should be avoided. While the lidar can operate at any elevation, Rayleigh and aerosol extinction in the lower atmosphere is considerable and better signal can be obtained at altitudes of about 2000-3000 m.

Scientific strengths Excellent vertical resolution; accurate and remote measurement of temperature. Lidars are essentially insensitive to tropospheric pollution. The DIAL approach is self-calibrating since a ratio of wavelengths is used.

Scientific weaknesses The method is sensitive to other absorbers, but these are unlikely to be present in sufficient quantities to produce serious problems. Even following major volcanic eruptions, the estimated error is only 1%. Weak absorption by NO_2 must also be considered, but this can be corrected for using empirical models and provides less than 0.3% error. At high altitudes (above about 35 km) where ozone absorption is weak, electronic noise is considerable and becomes the limiting factor in determining the absolute accuracy of present systems.

CNRS measurements

The group at CNRS has been measuring ozone in a research mode since 1983 and in an operational mode since October, 1986. More than a hundred ozone profiles have been obtained in the range from 25 to 45 km, allowing study of the absolute value and seasonal variations of the ozone content. Seasonal variations of the ozone concentration provide evidence for a transition between dynamical and photochemical regimes [*Godin et al.*, 1989]. Measurements of stratospheric aerosol have been carried out since 1982. Over 300 profiles have been obtained. The data obtained at OHP have been used to validate the aerosol measurements of the SAGE II instrument. The data were also used to establish a climatology of stratospheric aerosol and to correct Umkehr ozone data.

JPL

The JPL group has been involved with the construction of lidars for both stratospheric and tropospheric ozone specifically for the NDSC [*McDermid*, 1987]. The primary difference between the JPL system and that of Megie and co-workers or that used by the Japanese is the use of high-power laser systems and stimulated Raman scattering techniques to generate the reference wavelength for the stratospheric system [*McDermid*, 1987; *McDermid and Godin*, 1989] and both wavelengths for the tropospheric system [*Haner et al.*, 1988; *Haner and McDermid*, 1989]. The JPL ozone lidar has been used to collect more than 250 profiles from Table Mountain since January, 1988. The tropospheric ozone lidar is expected to measure ozone profiles from the ground to 20 km.

NASA GSFC

Under the auspices of the NDSC, the group at NASA Goddard Space Flight Center has developed a high-powered lidar instrument for the purpose of stratospheric ozone measurements. The primary difference between the GSFC lidar and the other NDSC lidars is that the Goddard system has been installed in a 44-foot trailer. The system uses a high-powered excimer laser for the ozone absorption wavelength and the third harmonic of a Nd-YAG laser for the reference wavelength [*McGee et al.*, 1989c]. The lidar system has been transported twice to the JPL Table Mountain Facility for the purpose of intercomparison withe the JPL lidar and other ozone measuring instruments (see, Section 2.5). Temperature data can also be retrieved from the reference lidar return.

2.2 Fourier Transform Infrared Spectroscopy (FTIR)

High resolution infrared solar absorption spectroscopy is a powerful tool for measurements of the column abundances of a variety of trace species in the Earth's atmosphere. Perhaps its greatest strength is the wide variety of species measurable. Except for monatomic species (He, Ar, Ne) and homonuclear diatomics (N_2, O_2, H_2) virtually all atmospheric species have rotational-vibrational absorption bands in the 2-14 mm spectral region (700-5000 cm^{-1}). Even N_2 and O_2 have weak but observable bands. Most species with average concentration greater than about 100 ppt have a detectable absorption, and in particularly favorable cases, species with concentration less than 2 ppt have been detected.

The technique consists of measurement of the direct spectrum of the sun at very high resolution (better than 0.002 cm^{-1} is intended for the Network instruments) at different solar zenith angles, generally near sunrise or sunset. High zenith angles give more absorption for very weak features, enhancing the detection limit, but in many cases interference by other species (particularly species with maximum mixing ratio in the troposphere) makes it impossible to observe at very large zenith angles [*Gao*, 1988]. Furthermore, for maximum precision of the measurement, it is desired to have features which are not saturated. For some abundant species, this means observations at zenith angles <60°.

Using laboratory measurements of line strengths and positions, the slant column abundance of various absorbers is determined, and this is converted to a vertical column. Knowledge, or assumption, of the vertical distribution of the absorber is required both for the determination of the slant column from the observed spectrum and for the conversion of the slant column to the vertical column. Uncertainty in the conversion to vertical column is minimized by using relatively small zenith angles.

Experience has shown that with good signal-to-noise (generally attainable in a few minutes observation), the precision in the retrieved column is better than 1% for species giving moderate absorption (say 25% peak absorption). Species with very weak absorption (e.g., $ClONO_2$) or with only continuous absorption (e.g., F-11) have poorer precision. The absolute accuracy is not nearly so good. It is limited by the uncertainty in the line parameters available (3-10% in many cases) and especially by errors in the temperature and mixing ratio profiles. Temperature errors are generally not very important, because it is possible to pick spectral lines for most species with little temperature dependence (≈1%/K), but errors in assumed profile can result in larger absolute errors, or poorer precision between days when the profile differs.

It is expected that the Network instruments will have a spectral resolution of 0.002 cm^{-1} or better, in order to obtain profile information from the shape of absorption lines. To minimize the variation of zenith angle during the collection of a single interferogram, time to collect the interferogram will be less than 1 minute; averaging spectra from several minutes observation will result in a signal-to-noise ratio in the spectrum of several hundred. The entire spectral region from 700-5000 cm^{-1} will be covered in a single or a few spectral intervals. Covering the entire range in a single scan can give problems due to atmospheric or instrumental modulation of total power, as well as detector linearity.

Table 1 lists most of the compounds that are expected to be observable by Network infrared spectrometers. Note that trends have already been measured in some species, particularly through observations from the Jungfraujoch [*Zander et al.*, 1987*a,b*]. The limitation on ground-based observations for many species is interference by tropospheric water vapor, which renders substantial frequency ranges (especially 1400-1800 cm^{-1}) opaque from the ground. For this reason, sites with low column water content and high altitude are needed for optimum infrared observation. An altitude of 1500 meters or greater will not only produce lower water columns, but also reduce pressure broadening and the total amount of tropospheric air in the column.

Several groups have been using FTIR from the ground, aircraft, balloons and space for two decades. It is expected that initially the network sites will be operated by some of these groups. One of the groups with longest experience is the Denver University (DU) group; it will be responsible initially for one or more sites. The group at Lauder, N.Z., (Matthews and coworkers) has been involved in collaborative work at Lauder, McMurdo, Antarctica, and Mauna Loa, Hawaii with the Denver group and will operate a new instrument in New Zealand and eventually Antarctica. R. Zander, of the University of Liége, has operated several instruments from the Jungfraujoch and will contribute measurements from the Jungfraujoch as a component of the Alpine site. The JPL group has operated interferometers from the ground at Table Mountain, Calif., as well as from balloons and aircraft [e.g., *Farmer et al.*, 1987; *Toon et al.*, 1989]. This group also carried out the Atmospheric Trace Molecule Spectroscopy (ATMOS) experiment onboard the space shuttle. Airborne measurements have been made by the National Center for Atmospheric Research (NCAR) group and the JPL group. A new laser heterodyne system is currently being developed in the UK (Woods).

Important points regarding the technique from the viewpoint of the NDSC:

Site Requirements FTIR measurements require an altitude minimum of 1500 m, as lower altitudes compromise many of the more difficult measurements including those of NO, NO_2 and

$ClONO_2$. Column water content less than 2 mm precipitable water is required. For polar observations, sites no further poleward than 80° are required in order to obtain a reasonable range of solar zenith angles year-round. The environment should be as cloud-free as possible, since a direct view of the sun unobscured by clouds provides the best measurements.

Scientific strengths A broad range of species can be measured with very high precision. High resolution, high signal-to-noise measurements may also provide some limited vertical profile information with approximately 1 scale height vertical resolution below about 30 km, based on observed line broadening. The information content requires further study.

Pollution The measurements are sensitive to tropospheric pollution. This can be a particular problem for HNO_3, HCl, NO_2 and O_3. For these species, information on the tropospheric abundances is highly desirable. Ancillary aircraft measurements may be required to identify tropospheric effects.

Supporting data needed The absorption features are, in general, strongly temperature sensitive. Therefore, information on the temperature profile is needed. This implies that the derived vertical column is also sensitive to the assumed profile shape.

University of Denver measurement activities

The group from the University of Denver conducted some of the first pioneering airborne measurements using infrared techniques, including for example, the first measurement of stratospheric HNO_3 from a balloon-borne platform [*Murcray et al.*, 1973]. They have obtained observations from many different platforms over the past decade, including recent observations from McMurdo Station, Antarctica in collaboration with the New Zealand group [*Murcray et al.*, 1989].

NCAR

The NCAR group has carried out airborne FTIR measurements from the north and south polar regions and many points between. Their measurements in Antarctica showed important changes in the abundances of many species influenced by polar stratospheric cloud chemistry, including the ratio between HCl and HF, the absolute abundances of NO and NO_2, and the abundance of $ClONO_2$ [*Mankin et al.*, 1989; *Coffey et al.*, 1989]. They also reported measurements of the column abundances of nitrogen species such as NO_2 and HNO_3 in mid- to high latitudes in the northern hemisphere [*Coffey et al.*, 1981], and documented an increase in stratospheric HCl following the eruption of the El Chichon volcano [*Mankin and Coffey*, 1983].

Jungfraujoch

A long record of IR measurements has been made since the mid-1970's and will continue at the Jungfraujoch. This group obtained the first measurements of stratospheric HF [*Zander*, 1975], a critical molecule for understanding anthropogenic halogen releases and their photochemistry. They have used their long-term series to determine trends in HF and HCl [*Zander et al.*, 1987*a*,*b*]. Further, they have analyzed data from the Kitt Peak observatory [*Zander et al.*, 1983], and have measured a broad range of stratospheric species including HCl, HF, and CH4 from balloon platforms [*Zander et al.*, 1981].

Table 1. Species measurable with FTIR

Odd Nitrogen Gases

Molecule	IR Detectability	Quality of Spectroscopic Data
NO	Good †	Good
NO_2	Good †	Good
HNO_3	Good	Fair
N_2O_5	Poor	Poor
HO_2NO_2	Poor	Poor
$ClONO_2$	Fair*	Fair

†Covered by H_2O absorption at low altitude sites

*Band of ν_3 fundamental at 6 μm detectable only under dry conditions from high-altitude sites.

Halogen Sink and Reservoir Gases

Molecule	IR Detectability	Quality of Spectroscopic Data
HCl	Good	Good
HF	Good	Good
COF_2	Fair *	Fair
HOCl	Poor	Good
ClO		

*Covered by H_2O absorption at low altitude sites.

Minor and Source Gases

Molecule	IR Detectability	Quality of Spectroscopic Data
O_3	Good	Good
H_2O	Good	Good
CH_4	Good	Good
N_2O	Good	Good
CO	Good	Good
CO_2	Good	Good
OCS	Good	Good
HCN	Good	Good

C_2H_6	Good	Fair
C_2H_2	Good	Good

Halogenated Source Gases

Molecule	IR Detectability	Quality of Spectroscopic Data
CCl_2F_2	Good	Poor
CCl_3F	Good	Poor
$CHClF_2$	Good	Poor
CH_3Cl	Poor	Fair
CH_3CCl_3	Poor	Poor
CCl_4	Fair	Poor
CF_4	Poor	Poor

Miscellaneous Gases

Molecule	IR Detectability	Quality of Spectroscopic Data
N_2	Good	Fair
O_2	Good †	Good
NH_3	Variable	Good
SF_6	Poor*	Good
OCS	Good	Good
HCN	Fair	Good

†Magentic dipole band at 1.27 µm

*Detectability affected by neighboring strong lines of CO_2 and H_2O. Background levels only measurable under dry conditions from high-altitude sites.

2.3 Ultraviolet and Visible Absorption Spectroscopy (UV/Vis)

The ultraviolet and visible instruments measure the absorption of incoming light from the sun, moon or zenith sky [*Brewer et al.*, 1973; *Noxon*, 1975; *McKenzie and Johnston*, 1983; *Mount et al.*, 1987; *Pommereau and Goutail*, 1988*a,b*]. The spectral data are then used to deduce slant column abundances of atmospheric absorbers, such as NO_2, given knowledge of the absorption spectrum based on laboratory measurements. The slant column abundances can be converted to vertical column abundances provided that the optical path, or "airmass" factor, is well understood. The airmass factor is determined from geometric considerations and is nearly independent of the vertical profile of the absorber when direct light from the sun or moon is used as the light source, but requires detailed consideration of atmospheric scattering when the zenith sky is the light source [*Solomon et al.*, 1987*a*]. Typical integration times range from

20 seconds near noon to 20 minutes at twilight using the zenith sky, and the spectral resolution is usually on the order of 0.5-1 nm. Measurements made using both the moon and sun allow diurnal information to be deduced for some species, such as OClO.

Optimum precision is achieved for species with the greatest number of strong spectral features. Absorption features present at the 1% level can be readily measured. Weaker features may also be measured depending on the detection system employed. The data analysis approach should include detailed consideration of all possible spectral features, e.g., in least-squares fashion [*McKenzie and Johnston*, 1983]. Possible interference between species should be evaluated in detail [see, e.g., *Solomon et al.*, 1989], particularly when a limited number of spectral features are observed. The absorption features in the visible and near-ultraviolet involve electronic transitions and thus are generally not very sensitive to temperature.

This technique as envisioned for the network allows measurement of the vertical column abundances of:

- NO_2 (estimated precision of measurement ≈ 1%)
- Ozone (estimated precision of measurement depends on the wavelength range and on the instrument. Can be as good as 1%).
- OClO and BrO, at least in polar regions (estimated precision ≈10%)
- NO_3 (night only, requires moon as the light source)
- Tropospheric water vapor
- Tropospheric O_4

Three groups are presently involved in UV/Vis measurements in association with the NDSC: the NOAA Aeronomy Laboratory in Boulder (Mount and co-workers), CNRS in France (Pommereau and co-workers), and the Department of Scientific and Industrial Research (DSIR) in New Zealand (Matthews and co-workers). The first two groups use diode array detectors, while the latter group employs photomultiplier tubes as their detector system. The use of diode arrays allows all the wavelengths of a chosen spectral region to be measured at once with high signal-to-noise ratios, facilitating detection of weak absorption features, while the photomultiplier allows for greater sensitivity at very low light levels.

Important points regarding the technique from the point of view of the network:

Site requirements: This is the only NDSC instrument that has no site requirement regarding elevation or tropospheric water content. The instrument can be operated at sea level. Zenith sky observations can be carried out in any weather condition, so that clear skies are not required unless direct sun or moon measurements are desired. This implies that the network measurements will not be biased with respect to tropospheric weather conditions. A monitor of sky conditions (e.g., all sky camera or time elapsed video) would be desirable for the network for studies of sky brightness fluctuations, which could yield useful information regarding atmospheric radiative transfer. However, for polar observations, sites no further poleward than about 75-80° latitude are required in order to obtain a reasonable range of solar zenith angles year-round. A clear view of at least one horizon is also required.

Calibration: Since the method utilizes the ratio of spectra, only a relative calibration of the spectral characteristics of the instrument is required. Only calibration changes that affect isolated regions of the spectrum where particular absorption features are located can affect the retrieved abundances, particularly for those instruments that use diode arrays. If the instrument suddenly changed sensitivity by some factor (dirty telescope window, for example), this would have no affect on the retrieved abundances.

Pollution: Insensitive to tropospheric ozone and NO_2 in clean to mildly polluted conditions, but highly polluted conditions cannot be tolerated for accurate stratospheric trend measurements.

Clouds: Measurements of stratospheric species such as NO_2 are insensitive to tropospheric clouds, but the influence of polar stratospheric clouds and heavy volcanic aerosols should be further investigated.

Scientific Problems: Unknown absorbers that can modify the absorption spectrum are the largest likely problem with this method. Amongst these, distortion of the spectral features due to the Ring effect must be considered a major difficulty, particularly for measurements of absorption levels below 0.1% [see *Solomon et al.*, 1987*a* and references therein].

NOAA Aeronomy Laboratory UV/Visible Spectrographs

The NOAA Aeronomy Laboratory group is developing UV/Vis instrumentation for all of the primary sites of the network. This group has previously made UV/Vis absorption measurements at a variety of sites including the Arctic and the Antarctic, largely using an instrument designed and built by A. L. Schmeltekopf. The instrument makes use of a diode array detector, allowing simultaneous observations over a wavelength range of about 50 nm at roughly 0.5 nm spectral resolution. The group has carried out measurements in the spectral range from approximately 330-450 nm and has demonstrated the ability to detect some species whose absorption lies in the range of 0.1% (such as OClO and NO_3). They have reported observations of O_3 [e.g., *Sanders et al.*, 1989], NO_2 [*Mount et al.*, 1987], OClO [*Solomon et al.*, 1987*b*], BrO [*Carroll et al.*, 1989], and NO_3 and H_2O [*Solomon et al.*, 1989].

The new instrument being built for application in the network has the following features:

- improved detector electronics. Estimated noise characteristics allow detection of absorption at the 0.02% level.
- double crossed 3/8 m focal length 1/7 Czerny-Turner
- approximately 50 nm simultaneous spectral coverage variable from ~ 0.3 to 1 μm

Five such instruments are presently being built and the first will be ready for use beginning in early 1991.

CNRS Diode Array Spectrographs

Pommereau and co-workers have developed an automated diode array system for UV/Vis observations. They have emphasized the fact that ozone absorption in the visible region is temperature independent, an important aspect of the utility of such measurements for the network [*Pommereau et al.*, 1989]. The instrument has recently been used to measure the Arctic NO_2 content from a variety of sites including Kiruna, Sweden, Sondrestromfjord in Greenland, and Dumont D'Urville in Antarctica [*Pommereau and Goutail*, 1988*a,b*]. The instrument employs real time processing and transmission.

The system is normally operated in the wavelength range from 290 to 590 nm at about 1 nm spectral resolution. The digitization of the diode array detector is different from that of the NOAA system and the instrument noise is estimated at about 0.1%.

DSIR Spectrometers

The group from DSIR has been involved in zenith sky measurements of NO_2 and ozone for many years using scanning spectrometers with photomultiplier detection systems. They reported the first long-term measurements of the stratospheric NO_2 content [*Johnston and McKenzie*, 1989] using their site in New Zealand. They also presented the first NO_2 measurements from the Antarctic continent [*McKenzie and Johnston*, 1984]; the importance of these measurements was recognized later when their role in polar ozone depletion was appreciated. Their instruments are currently operating in a monitoring mode at New Zealand (Lauder) and at several sites on the Antarctic continent including McMurdo/Arrival Heights and Halley Bay [*Keys and Johnston*, 1986; 1988].

2.4. Microwave Emission Spectroscopy

The microwave remote sensing technique involves making high spectral resolution measurements of optically thin pure rotational lines in atmospheric emission. The lines are generally pressure-broadened in the middle atmosphere, allowing information about the vertical profile to be deduced from measurements of the shape of the spectral line. Because the measurements are made in emission, observations can be carried out both day and night and diurnal information can thus be retrieved (especially for species such as ClO).

The basic measurement technique and accuracy have been discussed by *Parrish et al.*, [1988*b*], *Connor et al.* [1987], *Bevilacqua et al.* [1989], and *de Zafra et al.* [1987]. It is worthy of note that during the stratospheric ozone intercomparison campaign (Section 2.5), the scatter among 20-minute microwave ozone retrievals displayed a standard deviation as good as a few percent near 20 km, increasing to about 5% near 50 km.

The inversion techniques generally make use of optimal estimation and the Chahine method, although Rodgers' error analysis method is currently being used to characterize measurements and select algorithms. As measured by FWHM of averaging kernels, the height resolution is 6-7 km at best. In retrievals, resolution can be traded for precision, so that highest resolution may not be optimal for trend detection [see, e.g., *Brillet*, 1989].

Several groups are presently involved in the NDSC microwave measurement systems: Millitech Corporation/U. Mass (Parrish), NASA Langley Research Center (LaRC; Connor and co-workers), State University of New York at Stoney Brook (SUNY; deZafra/P. Solomon), Naval Research Laboratory (NRL; Bevilacqua/Schwartz), Pennsylvania State University (Olivero/Croskey), and one in France (De la Noe and co-workers). In addition, Kunzi in Germany and Kampfer in Switzerland are involved in ongoing ground-based measurements, particularly for ozone.

For the network, measurements will be made of the following species:

Species	Height Range	Time required	Est. precision
• Ozone	20-75 km	20 minutes	4%
• Water vapor	50-85 km	1 day	
	20-50 km	2 hours	6%
• ClO	25-45 km†	$\geq$1 day	10%

†Lower altitudes (down to about 15 km) are accessible during some seasons in polar regions, when ClO is greatly enhanced.

In addition, the following species have been measured with the microwave technique but are not currently targeted for NDSC measurement by the microwave method:

• HCN	25-45 km	≥ 1 day	5-10%
• N_2O	20-50 km	2 hours	
• CO	50-80 km	10-12 hrs	
• HO_2	35-50 km	>1 day	

HCN and N_2O are dynamical tracers for the stratosphere [see, e.g., *Parrish et al.*, 1988*a*; *Jaramillo et al.*, 1989]. Some dynamical tracer information is also provided by water vapor measurements, especially in the mesosphere [see *Strobel et al.*, 1987].

Site Requirements: Unobstructed view of the horizon to an elevation angle of at least 10°. Low tropospheric water vapor content, dependent on the species measured as follows:

Constituent	Frequency	Max. precipitable water (mm)
H_2O	22 GHz	31
O_3	110 GHZ	10
ClO	278.6 GHz	2
N_2O	275 GHz†	5
HO2	266 GHz	<2
CO	115 GHz	≈10

† This feature has been used for example, by *Parrish et al.* [1988*a*] but other spectral regions are under consideration.

A specific analysis by site carried out for the Geneva meeting suggests that H_2O measurements can be made at all of the proposed sites (with the possible exception of Tsukuba during summer) throughout the year with a measurement frequency greater than 50%. Ozone measurements can be made at all of the proposed sites throughout the year with the possible exceptions of Oslo and Perth in the summer. ClO measurements could only be made regularly at very good high altitude/latitude sites, such as Mauna Loa/Mauna Kea, the South Pole and the interior of Greenland. Except for summer, ClO measurements could probably be made with reasonable frequency in the southwestern U. S. (e.g., Kitt Peak, Mt. Hopkins, Sacremento Peak) and in Chile.

Measurements strengths: Vertical profile information; 24 hour operation; insensitive to local pollution and stratospheric aerosols.

Measurement weaknesses: Limited vertical resolution and decreasing sensitivity in the lower stratosphere (depending on the species distribution, but typically below 20 km for present instruments); long temporal averaging.

SUNY measurement activities

The group has been involved in millimeter wave measurements of many species from a variety of sites including Mauna Kea, Hawaii and McMurdo Station, Antarctica. They carried out ground-based measurements of ClO at Mauna Kea from time to time beginning in 1982 and at McMurdo Station in 1986. A permanent facility is being prepared at Mauna Kea for one of the NDSC ClO instruments. The diurnal and seasonal variations in lower stratospheric

Antarctic ClO were observed [*de Zafra et al., 1987*; *P. Solomon et al.*, 1987]. Their measurements of ozone showed that there is no significant seasonal decline in ozone above about 25 km over McMurdo Station, aiding in understanding of the altitude range affected by the ozone hole [*Connor et al.*, 1987]. Measurements of N_2O and HCN provided important Antarctic stratospheric tracer observations used to evaluate, and ultimately provide evidence against, dynamical explanations of the ozone hole [*Parrish et al.*, 1988*a*; *Jaramillo et al.*, 1989]. This group also presented the first remote measurements of stratospheric HO_2 [*deZafra et al.*, 1984] using the Mauna Kea observatory site.

Millitech/NASA Langley/U. Mass.

Millitech has built an ozone instrument and is presently developing a set of three ClO instruments for NDSC. These instruments employ the observing technique used in the older SUNY instrument [*Parrish et al.*, 1988*b*] but are specifically optimized for the NDSC. The calibration procedures will be mostly computer controlled to minimize operator attention. The ozone instrument uses the line at 110.8 GHz or 109.6 GHz. The ClO instruments use the line at 278.6 GHz. The ozone instrument was operated successfully at Table Mountain during the STOIC campaign in July, 1989 (Section 2.5). A collaboration has been established between NASA Langley and U. Mass. to process the data from the ozone instrument and others like it that are under consideration, but not yet built.

Naval Research Laboratory/Penn State University

These groups have devoted a great deal of attention to measurements of mesospheric water vapor. In particular, they provided some of the first measurements showing the rapid fall off of water vapor mixing ratio with altitude in the mesosphere [*Bevilacqua et al.*, 1983] and have carried out systematic measurements at several sites including JPL and State College, PA to characterize the seasonal trends and variability [*Bevilacqua et al.*, 1987; 1989]. Most of the previous water vapor measurements were made in the altitude range from 50-80 km. NRL is developing an instrument that will extend the lower limit of the altitude range down to the lower stratosphere (20 km). Penn State is developing a mobile instrument for intercomparison of observations at the various NDSC sites. Measurements of mesospheric CO have also been reported [e.g., *Bevilacqua et al.*, 1985] and provide useful information on mesospheric dynamics [*Solomon et al.*, 1985].

2.5 Results of the Stratospheric Ozone Intercomparison Campaign (STOIC 1989)

The first large scale, formal NDSC instrument intercomparison and evaluation of stratospheric ozone profiling instruments was conducted at the JPL - Table Mountain Facility in California (34.4°N) during July and August 1989. This intercomparison followed a much smaller scale, preliminary campaign also held at TMF during October and November of 1988 [*McDermid et al.*, 1989 *a, b*; *McGee et al*, 1989 *a, b*]. These studies have raised a number of general issues regarding NDSC operations and intercomparisons.

In addition to campaign type intercomparisons, there are several other methods of intercomparison, including comparison with mobile instruments, which may be used as transfer "standards" [*McDermid et al.*, 1989*b*], and long-term comparisons with satellite systems [*McDermid et al.*, 1989*c*] and other instruments within the station (e.g., microwave and lidar ozone). Two mobile instruments already designated for the network include a mobile lidar (GSFC), for ozone and temperature and a mobile microwave for H_2O (Penn. State).

The 1989 STOIC campaign was designed principally to evaluate the new instruments developed specifically for NDSC, i.e., the lidar and microwave systems for ozone. The groups and systems that participated in this intercomparison included the Millitech-LaRC microwave ozone, JPL and GSFC ozone lidars, NOAA and Wallops Flight Facility (WFF) Electrochemical Concentration Cell (ECC) balloon sondes, WFF ROCOZ-A rocket sondes, and the SAGE II satellite instrument. Every attempt was made to co-locate the measurements in both time and space. Thus, most of the measurements were made from TMF at a mean time around local (PDT) midnight. The exceptions to this were the ROCOZ-A rocket sondes, which were launched from San Nicolas Island (215 km south-west of TMF) and the SAGE II satellite measurements, which were at various locations within 1000 km of TMF. The ROCOZ-A and SAGE II measurements were also at different times from the TMF measurements. However, since the campaign was carried out during the summer at a mid-latitude site, it is expected that the observed variability largely reflects instrumental factors rather than atmospheric variability, which therefore allows detailed comparisons within the error limits. It should be noted that a time of higher atmospheric variability, such as the October - November 1988 campaign, can provide information on the ability of the various instruments to detect atmospheric changes and the effects of algorithms and range resolution.

STOIC was carefully conducted as a blind comparison and the results from each of the instruments were not circulated until after the end of the campaign. The blind data were compared and will be published as such. However, this blind intercomparison indicated some areas where the analysis algorithms could be improved and thus, a second set of results was compiled after refinements had been made (the lidars, microwave and NOAA ECC's provided a refined results set).

The results of the 1989 STOIC campaign are presently being prepared for scientific publication and only a few representative and summarizing results are shown here. There was only one day during the campaign, July 24, 1989, when all instruments made measurements. The individual profiles for this date are shown in Figure 1. This figure indicates that there is much overlap of the measurement ranges so that detailed intercomparisons can be made. To summarize the overall results from STOIC concerning the proposed NDSC instruments, Figure 2 shows the average of the ozone profiles measured during the two week STOIC campaign by the JPL lidar (JL), the GSFC lidar (GL) and the microwave (MM) compared with the average of all the instruments (STOIC). The agreement is such that it is difficult to discern the differences between the profiles on these plots. Therefore, Figure 3 shows the percentage difference of each of the individual instrument averages compared to the STOIC average. (Note: It should not necessarily be assumed that the STOIC average represents the true profile. Rather it provides a constant reference to assist in comparing a number of different instruments). It can be seen from Figure 3 that the ROCOZ-A results are 5 to 10% higher than the other instruments. While still not fully understood, the ROCOZ-A instrument has been seen to give higher ozone values in previous intercomparisons [*Barnes et al.*, 1987]. Using Figure 3, an altitude range can be defined for each instrument for which the agreement with the STOIC average profile is 5% or better. Thus, for the GSFC lidar, this range is 19.5 to 39.0 km; for the JPL lidar, 17.5 to 49.5 km; for the microwave, virtually its entire range from 20.5 to 63.5 km; for SAGE II, from 20.5 to 48.5 km. Within these ranges, there are also regions where individual instruments show agreement with each other with only 1 - 2% differences. The overall conclusion from STOIC is that a wide variety of different measuring techniques can show agreement at the 5% level when the measurements are made at approximately the same time of day and at the same location.

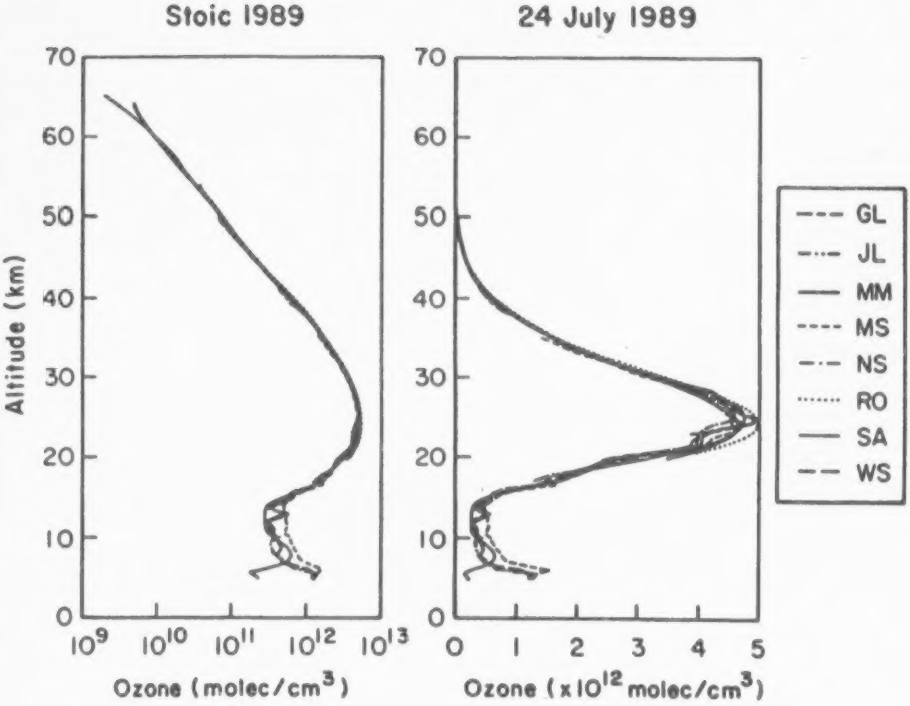


Figure 1. Ozone measurements near Table Mountain Observatory on July 24, 1989 by the JPL lidar (JL), the GSFC lidar (GL), the microwave (MM), the NOAA and Wallops ECC balloonsondes (NS and WS), the SAGE II satellite (SA) and the rocketsonde (RO).

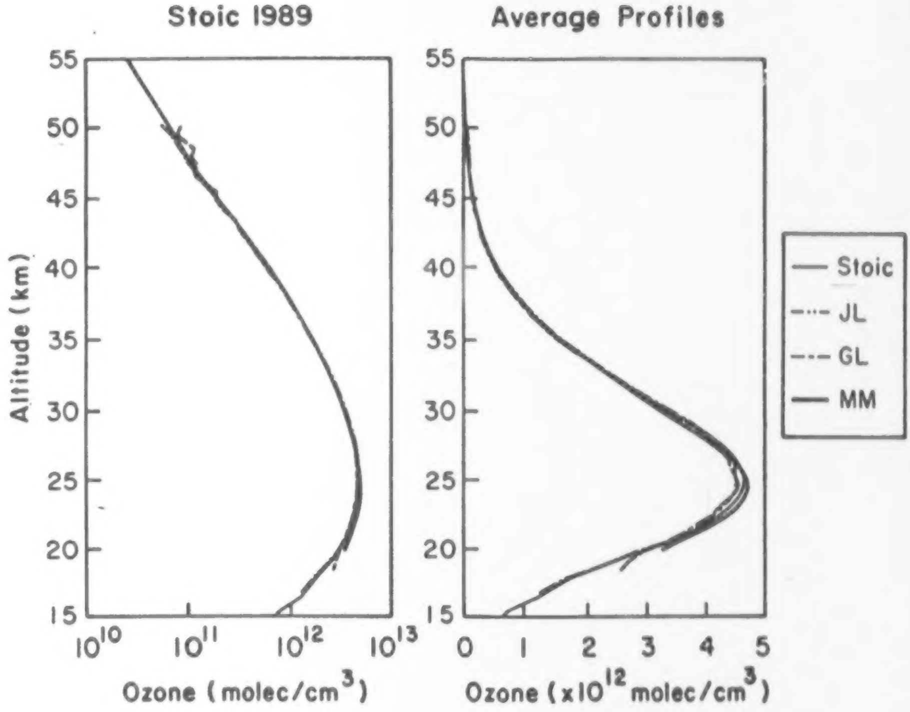


Figure 2. Average of the two week STOIC series of measurements by the JPL and Goddard lidars and the microwave compared with the average of all of the instruments (STOIC) during this period.

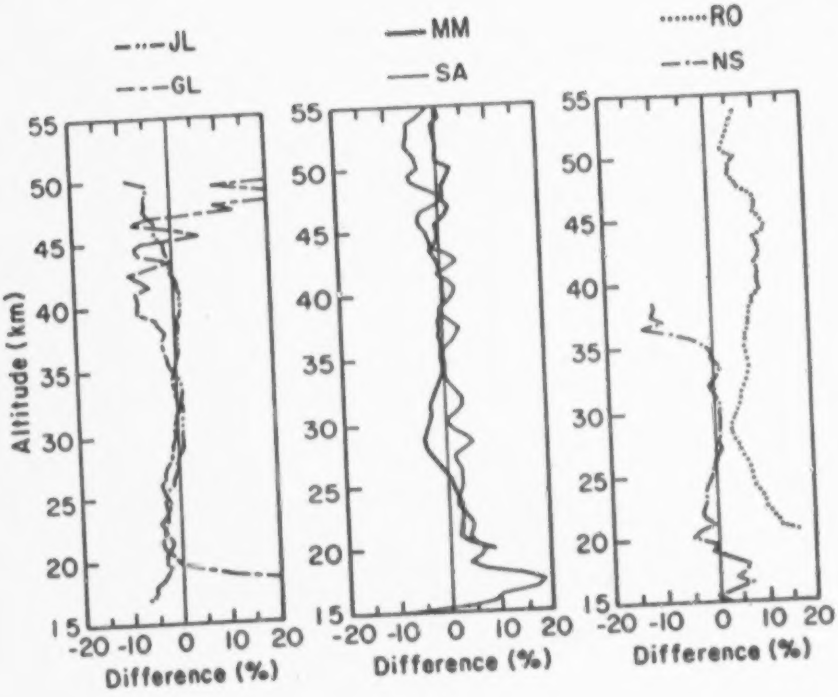


Figure 3. Vertical profiles of the percent difference of each of the individual instrument averages to the STOIC average.

3. Site Requirements

The general goal of detecting stratospheric trends in the Earth's atmosphere requires multiple sites of different types. At a minimum, three different types of air masses must be sampled:

- Polar
- Mid-latitude
- Tropical

Further, experience with the Antarctic ozone hole emphasizes the need for mid-latitude and polar measurements to be made in both hemispheres, requiring an absolute minimum of five sites.

Prior to the Geneva meeting, the French government proposed Haute-Provence as an NDSC station. More recently, the concept of a European mid-latitude station has been broadened to that of an Alpine station, which includes Haute-Provence as well as the Station Scientifique Internationale at the Jungfraujoch in Switzerland. In addition, NOAA proposed the use of Mauna Loa observatory in Hawaii. The Alpine and Hawaii stations should be provisionally considered network stations at this time. Mauna Loa observatory, while a subtropical rather than tropical site in the strict sense, provides a well-equipped facility where long-term monitoring is already underway for a variety of tropospheric trace gases and for Dobson measurements of total ozone. This suggests that an additional northern sub-tropical site at Mauna Loa would be both logistically feasible and scientifically valuable. The *IOTP* (1990) and *WMO* (1990) reports emphasized that northern hemisphere ozone trends exhibited significant dependence on longitude. Some of these trends are likely related to the climatological location of the sub-tropical jet stream and attendant meteorological patterns (e.g., the Aleutian high). These considerations suggest the need for additional mid-latitude sites.

From the viewpoint of satellite data evaluation, the following requirements should be considered:

- Vertical profiles of ozone in the stratosphere are of the highest priority.
- Tropospheric ozone data in both hemispheres is also critical for evaluation of total ozone trends and their origin.
- For SBUV, coverage in low latitudes in winter and summer is particularly needed.
- For SAGE, coverage in high latitudes in winter and summer is particularly needed.

3.1. Site Requirements Summary: Instrumental and Station

Summary of observational considerations:

- All instruments except the UV/Vis require an elevation of at least 2000 m. The microwave has the most stringent requirement if ClO is to be observed year-round, allowing only for the driest locations.

- Some instruments (IR, Lidar) require relatively clear skies, and some require a view of the horizon to an elevation of at least 10° (microwave) and in some cases to the horizon (IR).

- Some instruments require low pollution levels, particularly if species such as stratospheric NO_2 are to be observed (UV/Vis, IR).

- For polar observations, the IR and UV/Vis instruments require a site no further poleward than about 75-80° latitude in order to obtain a range of solar zenith angles year-round. This represents a possible conflict with the microwave, for which the South Pole represents a prime site because of its extremely low water vapor content.

A survey was taken at the 1989 Geneva meeting of the needs for each instrument in terms of power, space, etc. The resulting composite picture of a network station was used to evaluate needs for the Mauna Loa observatory site as an example (Tables 2 and 3).

It was assumed that the following instruments would be placed at the site:

(a) stratospheric ozone lidar (JPL)
(b) microwave ozone (Millitech)
(c) microwave ClO (Millitech)
(d) UV/VIS (NOAA)
(e) FTIR (DU)
(f) microwave water (NRL)
(g) tropospheric ozone lidar (NOAA)
(h) four visiting/additional instruments
(intercomparison, additional "invited" instruments, etc.)

This analysis provides a conservative estimate of needs, since it now appears that the microwave instruments may be placed at the Mauna Kea observatory, where they have operated in the past. From the questionnaires that most experimenters responded to at the Geneva meeting, a table of requirements was assembled (Table 2). From that table, a list of specific requirements for the new observatory building were drawn up (Table 3). In generating Table 2, room required between instruments both inside the building and on the roof was considered and increased power requirements were included to allow a margin for error. Area required in the new building other than for laboratory space was also estimated. Total building square footage is approximately 5000 sq ft. There will need to be a substantial roof with power receptacles and walking area for many of the instruments. Essentially all the experiments need roof access via some sized port down into the building laboratories. Power required is approximately 125 kw. Note that this estimate does not include building maintenance activities (A/C, heat, etc).

Possible interferences between instruments require good power insulation. Optical and electrical interferences may need to be considered on a case by case basis. Furthermore, possible interference with tropospheric clean air measurements must be borne in mind.

Personnel requirements are several technical people and an observatory manager. Lidar cooling requires a large flow of cooling water. Therefore, a closed cycle system will be required of the experimenters, since Mauna Loa has no water supply. Air exchange to the outside environment to dump heat will be needed, although some of the heat should be used to heat the building. Note that no 50hz power availability will cause problems for European experimenters.

Additional questions:

1) There is unlikely to be a view of both horizons from Mauna Loa. Can the eastern sun be viewed at all times of the year?

2) Is there a possibility of placing the horizon seekers (UV/Vis and FTIR) on Mauna Kea from which both horizons can be viewed?

TABLE 2. MAUNA LOA OBSERVATORY INSTRUMENT REQUIREMENTS

	SPACE (sq ft)			POWER			
INSTRUMENT	LAB	ROOF	STOR	BLDG	ROOF	GASES/WATER	PERSONNEL
O_3 LIDAR	250	100	50	110/5KW 220/15KW 480/2KW	110/1KW	20 l/min H_2O	1 FT
μwave O_3	200	X	30	220/3kw	X	1 l/day LN_2	2 TEMP, 1PT
μwave ClO	200	X	30	220/3kw	X	1 l/day LN_2	2 TEMP, 1 PT
UV/Vis	200	50	50	110/2kw	110/2kw	X	2 TEMP, 1 PT
FTIR	200	50	50	110/2kw 220/2kw	110/1kw	5 l/day LN_2	1 FT, 2 TEMP
μwave H_2O	250	3'x7'	50	110/18kw 220/1kw	X	1 l/day LN_2	2 TEMP, 1 PT
TROP O_3 LID	300	100	50	110/5kw 220/10kw	X	X	1 FT
VISITORS/ADDITIONAL INSTRUMENTS							
long term	2 labs available with generic facilities						
short term	2 labs available with generic facilities						
GSFC lidar		trailer unit		208 3ph;100A/ph			
PennSt H_2O		generic		110/2kw			
				220/3kw			
TOTALS*	2600	321	310	110/34KW 220/37kw 480/2kw	110/4kw	8 l/day LN_2 20 l/min coolant	3 FT (exp) 8 TEMP

special requirements:

(a) JPL lidar requires a 10-m separation of the telescope and the laser [Can it be folded together using mirrors?]
(b) Water cooling requires closed cycle coolers. Roof design for catchment of rain water is desirable.
(c) GSFC lidar power requirements are extremely large [Is this mobile instrument to be accommodated at MLO?]

+ preliminary requirements as turned in at Geneva meeting, 11/6/89

* without GSFC lidar requirements for power

TABLE 3. SUMMARY OF BUILDING REQUIREMENTS (PRELIMINARY) NETWORK FOR STRATOSPHERIC CHANGE - MAUNA LOA OBSERVATORY

DESCRIPTION	
Laboratory space:	
seven instruments	
four visiting instruments	11 x 300 = 3300 square feet
Restroom facilities:	150
Storage (repair parts):	
shipping crates and miscellaneous equipment	150
"garage storage" outside bldg	600
Repair Shop	150
Mechanical/AC/heat/UPS	location? (outside building?)
Computer/telecomm/FAX	200
TOTAL interior square footage	3950
outdoor	600+mechanical
Power: 110v/60hz/50kw	
220v/60hz/60kw	
480/60z/5kw	
total	115 kw

3.2 Current Site Selection Status

Several presentations were made in Geneva regarding additional possible sites for consideration. Some of the sites discussed were:

- The Japanese station at Tsukuba is already equipped with extensive lidar facilities and has the necessary scientific infrastructure. This station is rather cloudy and subject to high pollution and high water content, however.

- Among north polar sites, locations in Greenland appear to offer the best combination of access, existing infrastructure, proximity to the northern polar vortex and meteorological conditions. However, a prime concern was the tropospheric water content at low altitude sites. This question is currently being evaluated.

- The Canadian government is developing an Arctic ozone observatory at Alert. While at high latitude and in good proximity to the vortex, the station is at sea level. The latitude is too high for the FTIR and UV/Vis instruments.

- Spitzbergen is a site used for many observations by European investigators, and is being expanded as an Arctic site for European monitoring activities. While it provides good access, it is too far poleward and is climatologically far too cloudy for NDSC purposes.

- U. S. upper atmosphere researchers are developing sites at Poker Flat, Alaska and at Resolute Bay, Canada. Alaska lies in a particularly poor position with respect to the location of the north polar vortex and thus is probably not a viable choice, at least for the initial north polar site. Resolute Bay, on the other hand, is well located in terms of the polar vortex, but its tropospheric water vapor content should be evaluated in detail.

- Dome C may eventually provide an excellent combination of access, dryness and latitude for an Antarctic site. At present, McMurdo/Arrival Heights probably offers the best combination of existing infrastructure and access. The South Pole is preferable in terms of water vapor, but is at too high a latitude for some observations and is much less accessible over most of the year.

- An Australian representative proposed consideration of the site at Siding Springs, Australia (31°S), elevation 1000 m. The site is currently used for astronomical observations and has good access and local infrastructure.

- New Zealand has long had an active research group located at Lauder (45°S). The necessary scientific infrastructure and access exist, and the site is relatively pollution-free. Nearby mountainous locations offer the possibility of elevation of at least 2300 m. This site is undergoing evaluation as the third primary NDSC station following the Alpine and Mauna Loa/Mauna Kea stations.

- French researchers are planning to make use of a site at Reunion Island, a very high elevation location near 21°S in the southern hemisphere.

- U. S. researchers suggested consideration of sites within the continental United States as additional mid-latitude network sites. A summary of possible continental U. S. sites is presented in Table 4. Site characteristics are briefly outlined; possible interferences with existing measurement activities and the availability of space have not been examined at this time.

The steering committee has been charged with evaluating the candidate sites. The list of all sites currently under consideration is given in Table 5.

TABLE 4. POSSIBLE CONTINENTAL U. S. SITES

(a) **Mt. Evans, Colorado** - high altitude and low water vapor; extensively characterized by NCAR and DU for IR observations; no access during winter; no facilities on top. The eastern horizon is very polluted while the view of the western horizon is likely limited by mountains. Denver pollution presents a serious concern.

(b) **Echo Lake, Colorado** - developed DU site and extensively characterized by DU and NCAR for IR work; high elevation (11000 ft); horizon viewing is presumably good to the east and a few degrees in the west; low water vapor; on the divide so clear skies in morning and typically clouding in afternoon in summer, clear in winter; good access and logistical support. Denver pollution is a major problem.

(c) **Fritz Peak, Colorado** - developed NOAA site, probably will require a new building. No view of eastern horizon from main observatory area, but clear view to east from the top of Fritz Peak where a building already exists which could be refurbished to support the horizon seekers. Observatory or the building on the Peak give western horizons of a few degrees elevation due to mountains; good access and logistical support; easy airport access; skies generally clear since east of the divide, but often cloudy on summer afternoons, winter generally clear. Denver pollution on the eastern horizon is a major problem.

(d) **U. of Wyoming IR site near Laramie** - UW has a well developed IR site west of Laramie about 20 miles. Full logistical support and easy access; elevation about 9000 ft; view of horizon would depend on area selected (but probably only the eastern horizon); not near any major pollution source.

(e) **Table Mountain, California** - this site will undoubtedly have restricted use due to Los Angeles pollution; it can serve as an excellent instrument intercomparison and test/research site, however. The elevation is not sufficient for the microwave ClO instrument (i.e., precipitably water vapor) except for a few weeks during the year. Generally clear skies; easy airport access; well developed facilities and scientific support structure.

(f) **Kitt Peak, Arizona** - site of the largest astronomical observatory in the US; excellent access and logistical support; clear view of either horizon; low elevation (6000 ft); generally clear skies; Tucson pollution on eastern horizon.

(g) **Mt Graham, Arizona** - site being developed by U of Arizona. Elevation approximately 9000 ft, south of Tucson, presumably good logistical support.

(h) **Mt Hopkins, Arizona** - 10000 ft site already developed by the Smithsonian Institution for multiple mirror telescope system. Very small peak; South of Tucson; low pollution; possible limitations on horizon viewing should be investigated.

(i) **area near Socorro, New Mexico** - site of the Very Large Radio Telescope array; good logistical support at VLA; good elevation in mountains to west of Socorro (VLA is on plains); generally clear skies; no pollution source; no developed site where the actual station might be put; good view of eastern horizon but few degree elevation (at best) of the western horizon).

(j) **White Mountain, California** - The U of California uses this as a mountain research station and maintains year around access. Elevation is 14000 ft; view to the western horizon is >3-4 degrees due to the Sierra; view to east may not go to the actual horizon. Very clear skies year around and dirt road access after 50 miles of paved road from Bishop, CA in eastern California; long distance from a regional airport. Extreme working conditions at 14000 ft.

(k) **Sacramento Peak Observatory, New Mexico** - elevation 9000 ft in southern New Mexico; many buildings, as the site was formerly a US Air Force Observatory; large solar telescope now run by Kitt Peak National Observatory (National Science Foundation). Good horizon views (both horizons) ; low water vapor; excellent access from El Paso, Texas (about 75 miles); low pollution; excellent logistics already in place.

Table 5. CURRENT CANDIDATE SITES

Northern Hemisphere				Southern Hemisphere		
Polar	Mid-latitude	Subtropical	Tropics	Subtropical	Mid-latitude	Polar
Alert	***Alpine/Europe***	***Mauna Loa***	Nairobi	Reunion Is.	**Lauder**	South Pole
Spitzbergen	Tsukuba		Quito		Siding Spring	Halley Bay
Thule	Table Mtn†		Darwin		Argentina	Palmer
Poker Flat	Colorado/Arizona		Peru		Chile	McMurdo/Arrival Hts.
Resolute	California					Dumont D'Urville
						Syowa
						Vostok
						Dome C (1992)

Code:

† Currently used as an NDSC instrument test and research station
Bold Italic: Stations already chosen as NDSC sites
Bold underline: Stations likely to be chosen as sites

3.3. Additional Site Selection Criteria

3.3.1. Statistical

A statistical study can provide useful information on the representativeness of trend estimates and the nature of correlation of residuals for proposed network locations. Such a study was presented by *Tiao et al.* [1990], using monthly averaged time series of SBUV data divided into 10° latitude and 20° longitude blocks.

Figure 4 shows a plot of the resulting total ozone trend estimates, normalized with respect to Dobson ground data. This figure and other aspects of the analysis presented suggested that:

- Trends derived for the location of Mauna Loa are likely to represent fairly well those of the tropics. The correlation estimates between Mauna Loa and tropical locations were also shown to be high.
- Trends deduced at Antarctic stations poleward of about 65S exhibit low variability with respect to longitude. The opposite is true for north polar stations.
- Particularly high variability exists near 50-70N, where the largest range in trends was deduced from the satellite data.

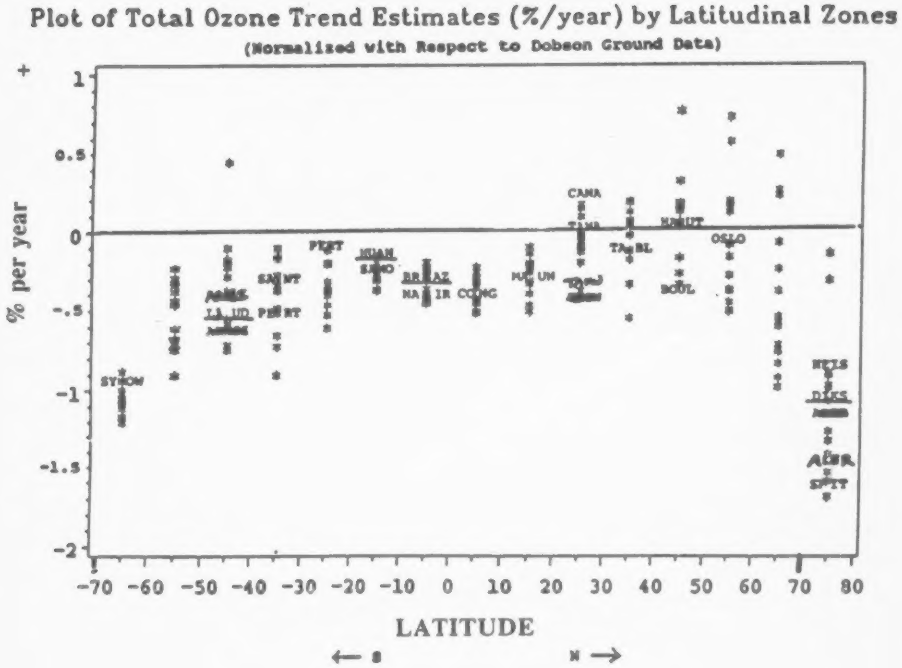


Figure 4. Total ozone trend estimates (%/year) by latitudinal zones based on statistical analysis of SBUV observations. The points corresponding to several existing sites used for various monitoring activities (e.g., OSLO) are indicated.

3.3.2. Meteorological Considerations

Frequency of measurements

In order to detect long-term changes in the stratosphere, the network must be able to estimate both dynamical and chemical trends. This means that observations must be taken often enough that high-frequency meteorological fluctuations (changes on daily to weekly time scales) can be characterized and the seasonal cycle can be determined. The latter allows for the later deseasonalization of the data and an estimate of interannual variability and long term trends.

Location of stations

From a meteorological stand point, the winter stratosphere can be characterized by three air mass regions: polar, midlatitude and tropical. These regions are delineated in part by mixing barriers, sharp potential vorticity (pv) gradients, which influence transfer of constituents between the air masses. The location of these barriers varies throughout the season; the polar barrier forms in fall, grows through winter, and decays in spring. Stations located near the mobile edge of these barriers (from a climatological standpoint) will show high constituent variance. It would therefore be preferable to locate stations away from the barrier edges. A minimum of five stations would be required to sample the different air masses: two polar (north and south), two midlatitude and one tropical station.

The tropical air mass is located between ± 30 degrees, with the subtropical jet providing the barrier. Unlike the polar pv barrier, the tropical barrier is less seasonal and less effective in the middle to upper stratosphere than it is near the tropopause. Station locations very close to the equator are preferred so that the meteorological variations associated with the quasi-biennial and semi-annual oscillation can be determined.

A final further consideration is that sample stations not be located near quasi-stationary meteorological features unless those features are being purposely studied. On the largest scale, stations should not be located beneath the Aleutian anticyclone (e.g. Alaska). On the mesoscale, station sites should be examined for the occurrence of persistent orographic gravity waves, which would needlessly increase the variance of measurements.

A preliminary analysis of most of the likely NDSC sites was carried out by M. R. Schoeberl and P. A. Newman (GSFC). Site temperatures and meteorological conditions in terms of the location of the polar vortex were evaluated using NMC data. It was shown that stations such as Pt. Barrow would be undesirable from the viewpoint of their location relative to the north polar vortex, while others such as Thule, Resolute and Alert had the best climatological proximity to the north polar vortex. Similarly, Syowa, Dumont D'Urville and Palmer are located on the edge of the south polar vortex, while others such as McMurdo/Arrival Heights, Vostok, Dome C, and the South Pole are more often inside the south polar winter vortex. Further study of the tropospheric water content and cloudiness will be conducted for each site under consideration.

3.3.3. Chemical Considerations.

The photochemical environment is expected to vary markedly with latitude and hemisphere. Thus it is clear that any attempt to detect trends must consider the latitude-dependent influences on quantities such as the ClO column abundance and its expected trends. A series of two-dimensional model calculations were presented in Geneva that provide a starting point for dealing with these issues. The model is basically that of *Ko et al.* [1985; 1989], updated to include current photochemical rates.

In the contemporary atmosphere, considerable latitudinal and seasonal variations in some chemical species are known to exist. Perhaps the best known of these is the large variation in column ozone abundance, varying from values as low as 120-220 DU in the Antarctic ozone hole and in the tropics to as high as 500 DU in north polar regions in spring.

Projections of the future state of the atmosphere were also carried out. The adopted scenario is summarized below. Some heterogeneous chemical processes were also considered in some simulations as indicated. Figures 5, 6 and 7 illustrate the calculated gradients in ClO, OClO, and $ClONO_2$ column abundances, with and without consideration of heterogeneous chemistry for the present day atmosphere. Note the very large latitudinal and seasonal gradients expected for all of these species, for example, in north polar regions. Observations of these seasonal variations by the NDSC stations and their comparison to multi-dimensional models will provide important information on the physical and chemical processes influencing the stratospheric variability.

Figures 8, 9, and 10 present calculated percent changes in O_3, ClO, and OClO between the year 1990 and 2000 for the chosen scenario, with and without consideration of heterogeneous processes. These estimates place important requirements on the accuracies needed for trend detection on this time scale. Note the very large estimated trends in polar regions for ClO and especially OClO (which depends on increases in both reactive chlorine and bromine).

Trend Study Summary (UNEP scenario B)

Year	Cl_x (ppbv)	Br_x (pptv)
1990	3.4	14
2000	4.2	17
2010	4.7	18

CH_4 trend ≈ 1%/year
N_2O trend ≈ 0.2%/year
CO_2 not included
No solar cycle included

Heterogeneous chemistry:

$N_2O_5 + H_2O \rightarrow 2HNO_3$ $\gamma = 5 \cdot 10^{-2}$
$HCl + ClONO_2 \rightarrow Cl_2 + HNO_3$ $k_{eff} = 3 \cdot 10^{-17}$

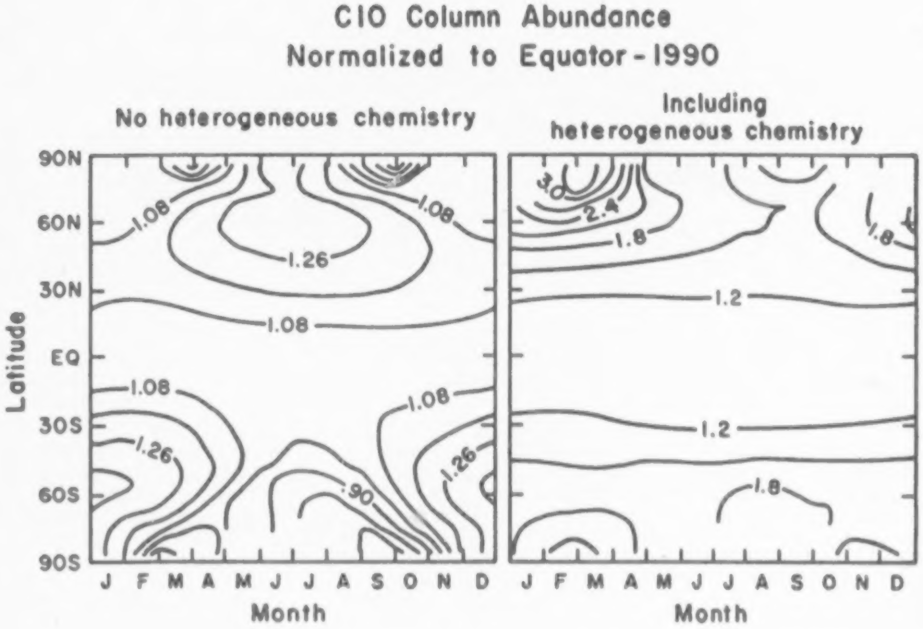


Figure 5. Calculated latitude gradients in the ClO column abundance relative to the equator from the two-dimensional model of *Ko et al.* [1985; 1989] for the year 1990, with and without consideration of the polar heterogeneous chemistry described in the text.

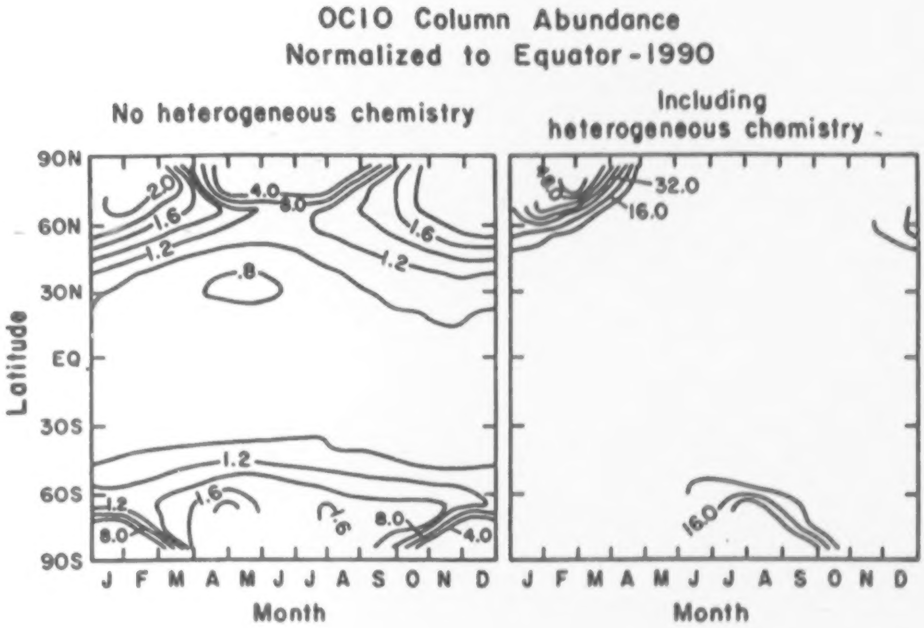


Figure 6. Calculated latitude gradients in the OClO column abundance relative to the equator from the two-dimensional model of *Ko et al.* [1985; 1989] for the year 1990, with and without consideration of the polar heterogeneous chemistry described in the text.

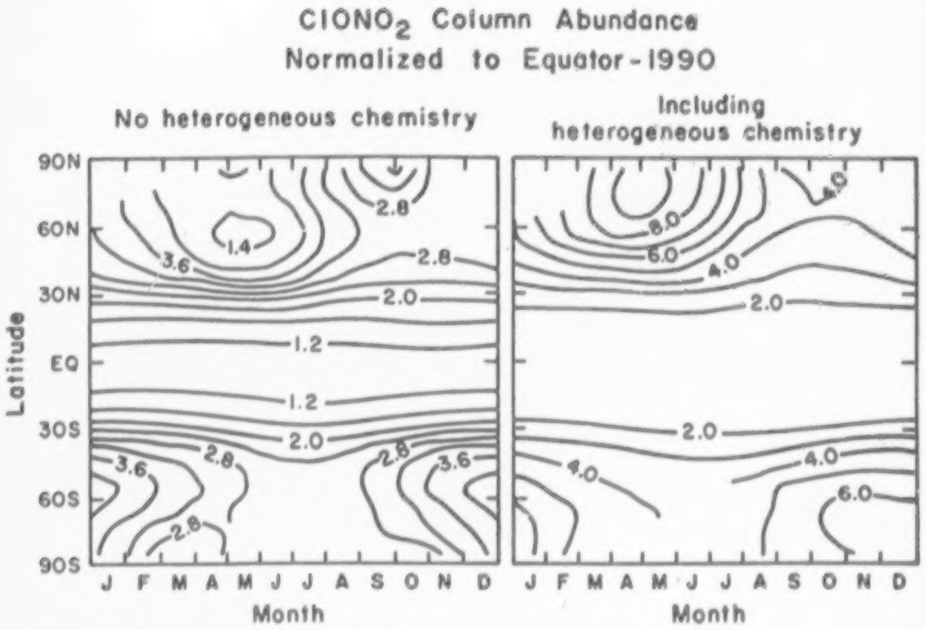


Figure 7. Calculated latitude gradients in the ClONO$_2$ column abundance relative to the equator from the two-dimensional model of *Ko et al.* [1985; 1989] for the year 1990, with and without consideration of the polar heterogeneous chemistry described in the text.

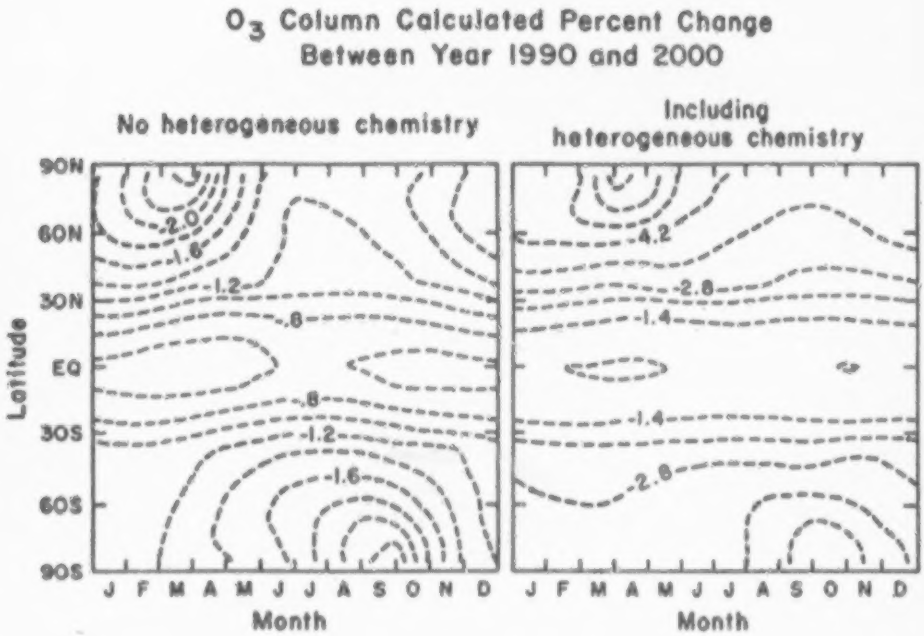


Figure 8. Calculated percent changes in the ozone column abundance between 1990 and 2000 from the two-dimensional model of *Ko et al.* [1985; 1989], for the trend scenario with and without consideration of the polar heterogeneous chemistry described in the text.

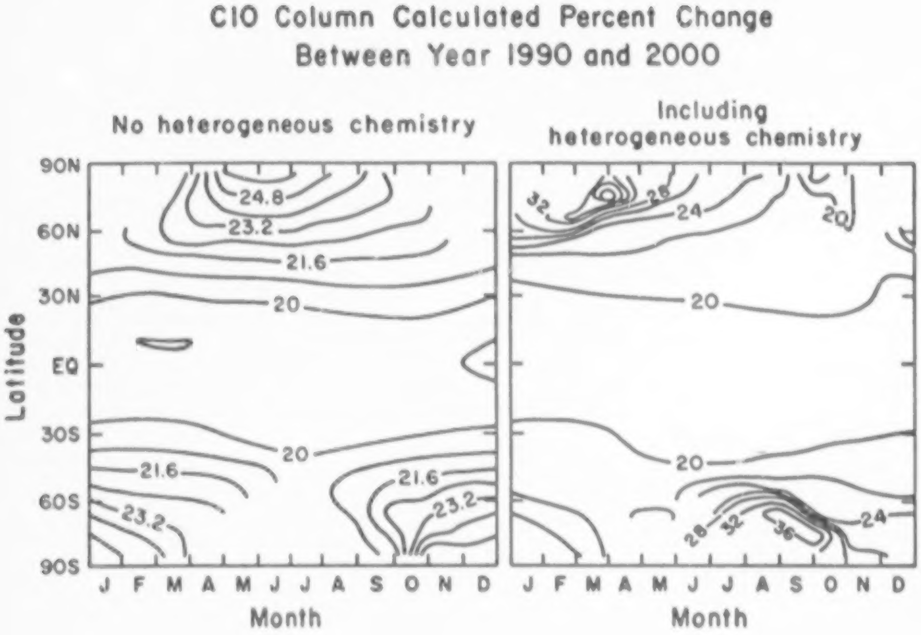
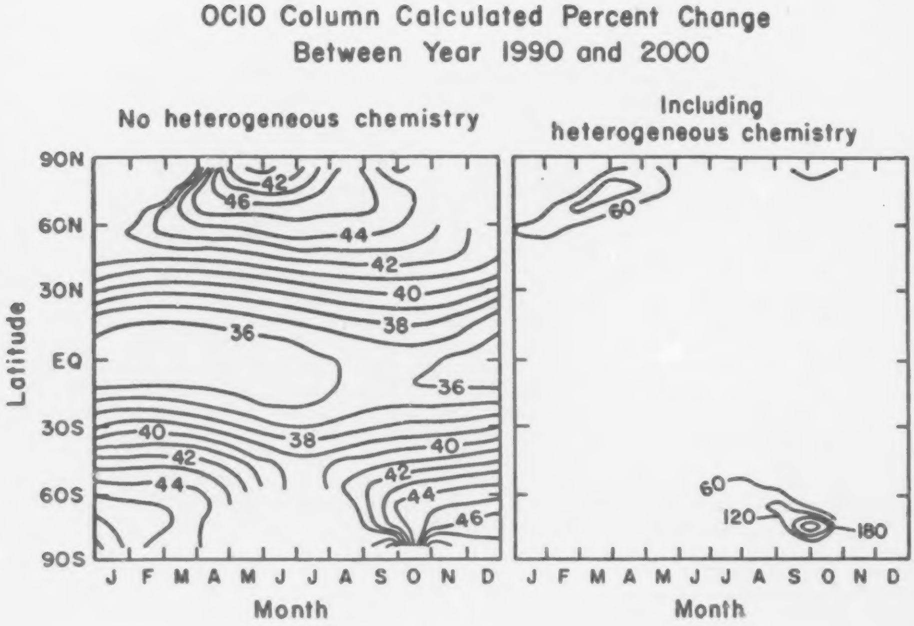


Figure 9. Calculated percent changes in the ClO column abundance between 1990 and 2000 from the two-dimensional model of *Ko et al.* [1985; 1989], for the trend scenario with and without consideration of the polar heterogeneous chemistry described in the text.



OClO Column Calculated Percent Change
Between Year 1990 and 2000

No heterogeneous chemistry

Including heterogeneous chemistry

Figure 10. Calculated percent changes in the OClO column abundance between 1990 and 2000 from the two-dimensional model of *Ko et al.* [1985; 1989], for the trend scenario with and without consideration of the polar heterogeneous chemistry described in the text.

4. Data Archiving

A first attempt was made at the Geneva meeting to assess NDSC needs for data archiving. The kind of data, timing of the data archival, location of the archived data set, format and other important issues were discussed.

There are several levels of data to be archived that may be described as follows: level 0 (raw data in counts or volts, uncalibrated), level 1 (calibrated data ready for use in retrievals to obtain geophysical parameters), level 2 (retrieved geophysical parameters such as temperature, ozone profiles, ozone column, etc.), level 3 (processed level 2 data, i.e., gridded data at common altitude points, monthly or diurnal averages, etc.). Level 0 data storage at each investigator's institution allows recheck of calibration software at any time. Level 1 data storage allows other researchers to use their own retrieval schemes if desired. An important question is whether FTIR interferograms should be archived, as these represent a considerable quantity of data (see below). Level 2 storage is assumed in all cases. Level 3 data will facilitate scientific investigations and intercomparisons. All level 1, 2, and 3 data from all NDSC sites will be archived in a central location. It is critical that each PI for a given instrument designate a team member who will interface with the archive manager and participate in the archival process in order to ensure correct archival and to identify problems.

Other supporting data that will be archived in level 0 are key calibration information, such as GMT time, scale factors, filter data and instrument field of view measurements. Ancillary data, such as meteorological information, will also be needed.

The issues of common NDSC data formats and gridding systems were also raised. Since the network data will be produced by a variety of instruments, some common data format is needed. There is no ideal standard data format (SDF). Experience has shown that as soon as one SDF is defined, another one is conceived. The best alternative appears to be a hierarchal or self-describing format wherein a header file describes what data follows and what form of storage is used for the data.

While it is clear that levels 2 and 3 data must be retained indefinitely, decisions must be made regarding how long to archive level 0 data. Other considerations for data archiving include how the data is to be accessed (e.g., from a central data bank, by mail or by phone lines) and what the data protocol is to be (see section 5). With respect to data accessibility, the recommended approach based on the Geneva discussions appeared to be a combination of electronic and storage medium access such as magnetic tapes, floppy disks, or optical disks which can be mailed to the user.

For each instrument, a rough estimate of data archiving requirements was carried out, the results of which are:

Lidar:

Single wavelength (one optical channel) 1 shot (analog and photon counting)
→ 30 kb
Acquisition time (7×10^5 shots), plus average over 1000 shots (4s to 100s)
→ 20 Mb
Dual wavelength measurements
→ 40 Mb

Assume 150-200 observations per year
→ 8 Gb/year for DIAL ozone measurements
→ 4-6 Gb/year for backscatter measurements
→ 30 Gb/year for raw data, from a single station

UV/Vis:

1 UV/Vis spectrum
→ 2500 bytes
Assume scattered sky and sun, one spectrum every 300 seconds during daylight.
→ 3.5 Kb/day
Assume one lunar spectrum every 300 seconds during moonlit periods (clear sky)
→ 3.5 Kb/day
→ 135 Mb/year for raw data, from a single station

Each spectrum results in 4 molecular slant column abundances and 4 molecular vertical column abundances
→ 5 Mb/year for level 2 data

Microwave:

Level	Storage (kbytes/day)
3 (summary)	10
2 (primary)	170
(auxiliary)	5
0 (raw - spectra)	50
(raw -calibration)	600
Total for 3 levels of storage:	835 kbytes/day

For 3-4 microwave instruments at a station, the total requirement is about 1 Gb/year.

FTIR:

Data rate = (Number of points•bytes/point)/time
= (spectral bandwidth•bytes/point)/(resolution•time)

Examples:

ATMOS = (4000 • 2)/(0.01 • 1) = 800 kb/sec
NCAR = (2000 • 2)/(0.03 • 6) = 22 kb/sec
Network = (2000 • 2/(0.002 • 60)= 33 kb/sec

Assume ≈40 kb/sec for the network.

Volume: 40 kB/sec • 3600 sec/hour • 1 hour/day • 200 operating days/year
→ 30 Gb/year

Summary of data storage requirements for all four instruments, per year, per station

Lidar	30 Gb
UV/Vis	0.14 Gb
Microwave	1 Gb
FTIR	30 Gb
GRAND TOTAL	61.14 Gb/yr/station

NDSC: Management

The organization of the NDSC was formalized at the Geneva, 1989 meeting and consists of a Steering Committee and a Science Team. The roles of each are outlined below:

A. Steering Committee

(1) Roles

The Steering Committee is the primary managerial body of the NDSC. As a representative group, it has the responsibility for such NDSC activities as:

Internal operational oversight,

Scientific oversight,

Recommending implementation and funding actions and,

Insuring that the needed working subgroups exist within the Science Team.

The Steering Committee addresses such diverse questions as:

Are the goals of the NDSC being met?

What should be the locations of new primary NDSC sites?

Which new instruments and PIs should be considered?

How to handle issues of data quality, tardiness in data reporting, etc.

The Committee is made up of a Chair, a Vice Chair, selected Principal Investigators, a group of Peers and Ex Officio members. The initial terms of the Chair, Vice Chair, Principal Investigators and Peers is 18 months and 30 months, with half of the terms ending at the first period and half ending at the second period. Staggered 24 month terms will occur thereafter. The nominations of persons for the initial membership are listed below and take effect upon the acceptance of the position by the nominee.

(2) Duties

The duties of the individual members of the Steering Committee are the following:

Chair and Vice Chair: These two are the lead oversight officials of the Steering Committee and are responsible for seeing the whole picture of the NDSC and share the following tasks: insuring measurement and interpretive coordination and tracking, promoting NDSC implementation, calling and presiding at Steering Committee meetings, and acting as Secretariat for the NDSC.

Principal Investigators: This set of about six of the NDSC PIs representing (for example, the various primary instrument types) ensures that the views of the Science Team (all PIs, as described below), are represented in the Steering Committee. While they would comment primarily from the perspective of their individual expertise (such as instrumentation, atmospheric science, or site management), they would be expected to speak the views of any of the Science Team members. An Alternate is associated with each of the Principal Investigators. The Alternate serves when the Principal Investigator cannot participate in a Steering Group activity. Subsequent members will be selected by the Science Team.

Peers: Operating in the mode of a standing review group, this set of members (equal in number to the Principal Investigators above), provides an independent voice in the affairs of the NDSC. They are scientists who are not Science Team members and are selected for possessing expertise that is highly relevant to the NDSC. Like the Principal Investigators, they would speak primarily from the perspective of their individual expertise, but they would be expected to comment across the spectrum of NDSC activities. After the initial set of Peers, the Ex Officio members will nominate a slate, from which the Science Team PIs will select new Peer members.

Ex Officio Members: This group consists of representatives of countries, agencies, or organizations that provide the support for the explicit NDSC activities associated with the implementation of the primary sites and the use of the resulting data. Included also are representatives of international organizations, such as WMO and UNEP. Currently, at the outset of the NDSC, this group is relatively small.

Initial Membership: The following names were nominated and accepted by the attendees at the organizational meeting in Geneva Switzerland on 6-8 November:

Chairman: M. Kurylo/NASA Headquarters
Vice Chair: A. Cox/National Environment Research Council, UK

Principal Investigators and Alternates:

LIDAR:	G. Megie/CNRS	(S. McDermid/JPL)
UV/Vis:	A. Matthews/DSIR	(J. Pommereau/CNRS)
Microwave:	R. Bevilacqua/NRL	(J. De La Noe/Observatoire de Bordeaux)
FTIR:	W. Mankin/NCAR	(R. Zander/U. Liege)
Theory:	S. Solomon/NOAA	
Satellite:	J. Miller/NOAA	

Peers:	C. Rodgers/Oxford University J. Russell/NASA V. Khattatov/Central Aerological Observatory, Moscow M. Schoeberl/NASA GSFC W. Hill/Allied Chemical plus one yet to be named
Ex Officio:	R. Watson/NASA Headquarters D. Albritton/NOAA L. Gray/AFEAS FP(CMA) R. Bojkov/WMO P. Usher/UNEP

B. Science Team:

(1) Role:

The function of the NDSC Science Team is to provide the forum for conducting the business of the NDSC. It will operate primarily within a set of subgroups organized around specific topics of the NDSC. Examples of subgroups that are of likely utility are:

Instrument Type (e.g., lidar, microwave, IR, UV/Vis, etc.)

Molecule Addressed (e.g., O_3, NO_2, Cl-containing, etc.)

Function (theoretical analysis, data archiving, calibration, intercomparison, satellite/NDSC interaction, size management, other network coordination, etc.)

(2) Membership:

There are one or two PIs associated with each of the instrument types at the primary NDSC sites. These PIs constitute the Science Team.

The current PIs are the ones that, over the past year or so, proposed for and obtained support for the specific NDSC activity. The addition of new PIs will be a joint enterprise between the Steering Committee and supporting organizations (via their Ex Officio members). The supporting organizations generally have their own peer review process, as well as taking due cognizance of the views of the Steering Committee.

Most of the activities associated with the principal instruments of the NDSC sites will have associated personnel, (e.g., scientific coworkers or analysts). These colleagues are Co-Investigators in the NDSC organization and will play major roles in many of the Science Team's subgroups.

Data Protocol

The Network's data lie at the heart of its contribution to understanding stratospheric change. As with any good research, the PIs bear the responsibility for its quality. The use of the data will follow a protocol, the main features of which are summarized here.

The protocol recognizes three time periods, the lengths of which will require further discussion and acceptance. The time periods in parantheses were used as examples in the Geneva discussions:

(1) PI Focus (from measurement to 1 year)

- The PIs reduce and analyze their own data
- The PIs can publish their own data, or release it to other researchers of their choice
- At or before the end of this period, the PIs turn in their data to the NDSC

(2) NDSC Focus (from measurement to 2 years)

- Any of the NDSC PIs can use any of the NDSC data, but must offer coauthorship with the PI whose data are used

(3) Community Focus (after 2 years)

- The NDSC data is openly available to the international scientific community.

Special cases will no doubt arise. Exceptions to the above will warrant discussion by the Steering Committee. Examples are campaigns in the vicinity of a Network primary site for which early access to the Network data would promote the goals of the campaign or geophysical episodes for which the Network data could be useful in planning the research response.

Near-Term Topics for Steering Committee Consideration

At the Geneva meeting, several topics were identified as ones that required early consideration by the Steering Committee. They are given here roughly in priority order:

- Evaluation of the Lauder, New Zealand location as the Southern Hemisphere midlatitude NDSC site. Discussions of potential Northern Hemisphere high latitude sites and a tropical site are also needed.

- The list of PIs that are involved at the primary Network sites should be established. These are the initial members of the Science Team. Co-Investigators should also be identified.

- The procedures for formal affiliation of theorists on the science team need to be defined.

- The draft data protocol needs to be finished and agreed upon by all NDSC PIs as conditions of their acceptance into the network.

- Draft plans for the Mauna Loa (Hawaii, USA) NDSC site need to be assessed.

- The membership of the steering committee needs to be completed.

- Complementary interfaces with other measurement programs need to be developed.

APPENDIX

I. Roles of each agency/organization involved in the NDSC

There exists mounting evidence that the Earth's ozone layer is changing on a nearly global scale. Although the most pronounced decreases are presently limited in geographic extent to certain latitudes and exhibit significant seasonal variability, the findings have sparked intense scientific interest in a worldwide network for the measurement of stratospheric change. The feasibility of such an initiative has been supported by recent developments in ground-based measurement technology for the detection and interpretation of ozone changes. Thus, the Network for the Detection of Stratospheric Change (NDSC) has arisen from the interest and involvement of the individual scientists who make up the international scientific community engaged in stratospheric research. Important organizational impetus for the NDSC has been provided within the United States by NASA and NOAA.

The core of the NDSC is the Science Team: the scientists who will build and deploy the instruments, and use and interpret the data. The principal investigators presently involved in the NDSC within the United States include scientists from NASA, NOAA, and other U.S. government laboratories (such as the Naval Research Laboratory and the National Center for Atmospheric Research); several different U.S. universities (including SUNY/Stoney Brook, Denver University, and the Pennsylvania State University); and one private corporation (Millitech). Scientists at foreign government laboratories including the Centre Nationale de Recherche Scientifique (CNRS) in France and the Department of Scientific and Industrial Research (DSIR) in New Zealand are also directly involved in the NDSC, along with researchers at foreign universities such as the Universite de Bordeaux in France and the Universite de Liege in Belgium. Each of these organizations has recognized the need for a long-term commitment in the NDSC to provide instrumentation and/or site facilities as well as the human operational resources. The scientific burden is thus shared by many nations and the cost burden is borne by several national and international sources. Financial support for the NDSC within the United States currently comes primarily from NASA, NOAA, and the Chemical Manufacturers Association (CMA). In addition, the National Science Foundation (NSF) has provided important support for NDSC-related activities in Antarctica. The list of individual participants and institutions is expected to grow significantly in the near future, thereby broadening the scientific and resource base for the NDSC.

The NDSC is governed by a Steering Committee chaired by M. J. Kurylo of NASA (and the National Institute of Standards and Technology) and R. A. Cox of the National Environmental Research Council (NERC) in the United Kingdom. Steering Committee members include representatives from NASA, NOAA, CMA, the above-mentioned Science Team, and other international universities and laboratories including the Central Aerological Observatory in Moscow. Thus, this managerial body is a truly international group with broad-ranging expertise and representation.

II. Time lines for construction and operation

A fully operational NDSC will consist of at least five primary stations worldwide (covering both the Northern and Southern Hemispheres). At present, two such stations have been definitely identified: an Alpine station in Europe consisting of several measurement sites, and a station consisting of Mauna Loa and Mauna Kea in Hawaii. A full instrument complement is expected to be in place at the Alpine Station by late 1991 or early 1992, enabling systematic NDSC operation to begin in 1992. Construction modifications at the Mauna Loa facility will begin in 1990/91 with the goal of complete instrument deployment at Mauna Loa/Mauna Kea by mid-1992. Thus, full NDSC operations should begin at the Hawaii Station by the end of 1992 or early 1993.

Candidates for the remaining sites are currently being evaluated. Following a rigorous site selection process, instruments will be built, tested, and deployed at each station as rapidly as possible. It is hoped that a five-station network will be completely operational by the 1993/94 time frame. There are also likely to be several "secondary stations" (with a more limited component of instruments) that will be selected for participation in the NDSC. The operation of these stations will be phased into the NDSC following detailed evaluation and analysis of the instruments and site characteristics.

III. Cost estimate (1990 $'s)

Equipment costs for each of the five primary stations are estimated to be at least $3M, for a five station total of at least $15M. Other capital costs for primary station facilities development range from near zero to more than $1M per station depending on the degree of new fabrication that will be required at some of the more remote stations. In addition, yearly operational costs are expected to be in the $2M range for each primary station. Costs for secondary stations will vary depending on the size of the instrument complement at each one.

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NDSC MAILING LIST

Dr. Daniel Albritton
NOAA Aeronomy Laboratory
325 S. Broadway
Boulder, CO 80303

☎ Tel: 303-497-5785
Fax: 303-497-5373

Dr. Alain Barbe
Universite de Reims
Laboratoire de physique moleculaire
REIMS
France

☎ Tel: 26 053.258
Fax: 26 053.279

Dr. Robert A. Barnes
Chemal, Inc.
P.O. Box 44
Wallops Is., VA 23337

☎ Tel: (804) 824-1637
Fax: (804) 824-1036

Dr. James W. Barrett
ESS Dept.
State Univ. of New York
Stony Brook, NY 11794-2100

☎ Tel: (516) 632-8207
Fax: (516) 632-8240

Dr. Richard Behnke
NSF
1800 G. Street, N. W.
Washington, DC 20550

☎

Dr. Richard Bevilacqua
Naval Research Laboratory
Code 4033B
Washington, D. C. 20375

☎ Tel: (202) 767-0768

Dr. Rumen Bojkov
WMO
P. O. Box 2300
Geneva 2
Switzerland

☎ Tel: 4122 7308.455
Fax: 4122 7342.326

Dr. Allan I. Carswell
Institute for Space and Terrestrial Science
4850 Keely Street
North York, Ontario
M3J3K1 Canada

☎ Tel: (416) 665-5417
Fax: (416) 665-2032

Dr. Michael Coffey
NCAR
P.O. Box 3000
Boulder, CO

☎ Tel: (303) 497-1407
Fax: (303) 497-1137

Dr. Brian J. Connor
NASA Langley
MS 401B
Hampton, VA 23665

☎ Tel: (804) 864-5698
Fax: (804) 864-6326

Dr. R.A. Cox
Marine and Atmospheric Sciences Directorate
NERC Headquarters
Polaris House, North Star Ave.
Swindon, Wilts SN2 1EU UK

☎ Tel: (44) 793-411694
Fax: (44) 793-411545

Dr. Charles Croskey
Pennsylvania State University
CSSL
304 EEE, University Park
Pennsylvania 16802

☎ Tel: (814) 865-2357
Fax: (814) 865-7065

Dr. J. De La Noe
Observatoire de Bordeaux
B. P. 89
F-33270 Floirac, France

☎ Tel: 33-56-864-330
Fax: 33-56-404-251

Dr. L. Delbaouille
Institut d'Astrophysique
Univ. de Liege
5, avenue de Cointe
4200 OUGREE-LIEGE, Belgium

☎

Dr. Dieter Ehhalt
Inst. fur Atmos. Chemie KFA
Postfach 365
Julich, W. Germany 517

☎

Dr. Eldon E. Ferguson
Climate Modeling and Diagnostics Lab
NOAA
Boulder, CO 80303

☎

Dr. Giorgio Fiocco
Univ. "La Sapienza"
Physics Department
00161 ROME
Italy

☎ Tel: 39 64 453245
Fax: 39 64 493158

Dr. Herbert Fischer
Kemforschungs Zentrum
Karlsruhe, GMbH
P. O. Box 3640
D-7500 Karlsruhe-1, FRG

☎ Tel: 07247-823643

Dr. Brian G. Gardiner
British Antarctic Survey
Madingley Road
CAMBRIDGE CB3 OET
UK

☎ Tel: 44 223 61188
Fax: 44223 62616

Dr. Aaron Goldman
Department of Physics
University of Denver
Denver, CO 80208

☎ Tel: (303) 871-2897
Fax: (303) 871-4000

Dr. Linsley Gray
Akzo Chemicals, Inc.
8401 W. 47th St.
McCook, IL 60525

☎ Tel: (708) 442-7100
Fax: (708) 442-1018

Dr. S. Godin
Service d'Aeronomie
Universite Pierre et Marie Curie
Tour 15 5e Etage, 4 Place Jussieu
75230 PARIS CEDEX 05, France

☎ Tel: 331 4354.1812
Fax: 331 4354.2031

Dr. David Griffith
Dept. of Chemistry
University of Wollongong
P.O. Box 1144
Wollongong, NSW 2500, Australia

☎ Tel: 042 270 515
Fax: 042 270 114

Dr. Massimo Del Guasta
IROE
Via Panciatichi 30
Florence, Italy

☎

Dr. Gordon Keys
PEL Lauder DSIR
Lauder C.O.
9182 New Zealand

☎ Tel: (64) 3 4473.339
Fax: (64) 3 4473.348

Dr. Vyascheslav Khattatov
Central Aerological Observatory
Dolgopurdney
Moscow Region, USSR 141700

☎

Dr. Olli Koistinen
Helsinki University of Technology
Radio Laboratory
Otak. 5A
02150 ESPOO, Finland

☎ Tel: 358 04512256

Dr. Walter D. Komhyr
NOAA/ARL/GMCC
R/E/AR4
Boulder, CO 80303

☎ Tel: (303) 497-6331

Dr. Klaus F. Kunzi
University of Bremen
PO Box 330440
2800 BREMEN 33
Federal Republic of Germany

☎ Tel: 49 421 218.3909
Fax: 49 421 218.3601

Dr. Michael Kurylo
NASA Headquarters
Code EEU
Washington, DC 20546

☎ Tel: (202) 453-1681
Fax: (202) 755-2552

Dr. R. Lauque
Observatoire Bordeaux
B.P. 89
33270 FLOIRAC
France

☎ Tel: 56 864 330
Fax: 56 404 251

Dr. John Lynch
NSF/DPP
1800 G. Street, N. W.
Washington, DC 20550

☎

Dr. Jerry Mahlman
NOAA/Geophysical Fluid Dyn. Lab.
Princeton, NJ 08542

☎ Tel: (609) 452-6502

Dr. William Mankin
NCAR/ACD
P. O. Box 3000
Boulder, CO 80307

☎ Tel: (303) 497-1403
Fax: (303) 497-1137

Dr. Andrew Matthews
PEL Lauder DSIR
Lauder C.O.
9182 New Zealand

☎ Tel: (64) 3 4473.339
Fax: (64) 3 4473.348

Dr. M. P. McCormick
NASA LaRC
Aerosol Research Branch
Hampton, VA 23665

☎ Tel: 804-864-2669
Fax: 804-864-2671

Dr. Stuart McDermid
JPL
Table Mountain Facility
Wrightwood, CA 92397-0367

☎ Tel: (619) 249-4262
Fax: (619) 249-5392

Dr. Thomas J. McGee
NASA/GSFC Code 615
Greenbelt, MD 20771

☎ Tel: (301) 286-5645
Fax: (301) 286-2630

Dr. Richard McPeters
NASA/GSFC Code 616
Greenbelt, MD 20771

☎ Tel: (301) 286-3832

Dr. Gerard Megie
Service D'Aeronomie CNRS
T15-E5, Universite Pierre et Marie Curie
4, Place Jussieu
75231 Paris CEDEX 05 FRANCE

☎ Tel: 33-1-4354-8887
Fax: 33-1-4354-2031

Dr. John Meriwether
AFGL/LID
Hanscom AFB, MA 01731

☎ Tel: (617) 377-3045

Dr. A. J. Miller
NOAA/NWS
5200 Auth Road
Washington, D. C. 20233

☎ Tel: (301) 763-8071
Fax: (301) 763-8381

Dr. George Mount
NOAA Aeronomy Laboratory
325 Broadway
Boulder, CO 80303

☎ Tel: (303) 497-3571
Fax: (303) 497-5373

Dr. Jarvis Moyers
NSF
1800 G. Street, N. W.
Washington, DC 20550

☎

Dr. Frank Murcray
University of Denver
Dept. of Physics
Denver, CO 80208

☎ Tel: (303) 871-2627
Fax: (303) 778-0406

Dr. John Olivero
Department of Meteorology
Penn State University
509 Walker
University Park, PA 16802

☎ Tel: (814) 863-1580
Fax: (814) 865-3663

Dr. Alan Parrish
Millitech Corp.
Box 109
South Deerfield, MA 01373

☎ Tel: (413) 665-8551
Fax: (413) 665-2536

Dr. Dieter Perner
Max Planck Institute
Postfach 3060
D-6500 Mainz, FRG

☎

Dr. C. M. R. Platt
CSIRO
Div. of Atmos. Research
P. Bag 1
Mordiallos, VIC 3195 Australia

☎

Dr. Uli Platt
Dept. of Physics
University of Heidelberg
Heidelberg, FRG

☎

Dr. Jean-Pierre Pommereau
Service d'Aeronomie -BP3
Verrieres le Buisson
France 91371

☎ Tel: 331 64 474.288
Fax: 331 69 202.999

Dr. Michael Proffitt
NOAA Aeronomy Laboratory
325 S. Broadway
Boulder, CO 80303

☎ Tel: (303) 497-3345
Fax: (303) 497-5373

Dr. John Pyle
Department of Chemistry
Lensfield Road
Cambridge, UK

☎ Tel: 44-223-336473

Dr. Curtis Rinsland
Atmospheric Sciences Division
NASA Langley Research Centre
Mail Stop 401A
Hampton, VA 23665-5225

☎ Tel: (804) 864-2699
Fax: (804) 864-3800

Dr. Clive Rodgers
Dept. of Atmos. Phys.
Clarendon Laboratory
Oxford OX1 3PU UK

☎ Tel: 44 865 272905
Fax: 44 865 272923

Dr. Howard Roscoe
British Antarctic Survey
Madingley Road
CAMBRIDGE CB3 OET
UK

☎

Dr. James M. Russell III
NASA Langley Research Center
Code 401B
Hampton, VA 23665

☎ Tel: 804-864-5691

Dr. Ryan W. Sanders
NOAA Aeronomy Laboratory
325 S. Broadway
Boulder, CO 80303

☎ Tel: (303) 497-3057
Fax: (303) 497-5373

Dr. Yasuhiro Sasano
National Inst. for Environ. Studies
Tsukuba
IBARAKI 305
Japan

☎ Tel: 298 51.6111
Fax: 298 51.4732

Dr. Erwin Schanda
Institut fur Angewandte Physik
Universitat Bern
Sidlerstrasse 5
CH-3012 BERN, Switzerland

☎ Tel: 031-65-89-10

Dr. Mark Schoeberl
NASA GSFC
Code 616
Greenbelt, MD 20771

☎ Tel: 301-286-5819

Dr. P. R. Schwarz
NRL Code 4033
Washington, DC 20375-5000

☎ Tel: (202) 767-3391

Dr. Wolfgang Seiler
IFU
Kreuzeckbahnstr. 19
8100 GARMISCH-PARTENKIRCHEN
FRG

☎ Tel: 8821-18310
Fax: 8821-73573

Dr. Parthasarathy Shakkotta
JPL
Mail Stop 125-214
4800 Oak Grove Dr.
Pasadena, CA 91109

☎

Dr. Robert J. Sica
Physics and Astronomy Building
University of Western Ontario
London, Ontario, N6A 3K7 Canada

☎ Tel: (519) 679-2111 x 6509
Fax: (519) 661-2033

Dr. Paul C. Simon
Institut d'Aeronomie Spatiale
3 av. Circulaire
1180 BRUSSELS
Belgium

☎ Tel: 322 375.1579
Fax: 322 374.8423

Dr. Philip Solomon
Earth and Space Sciences
State University of New York
Stony Brook, NY 11794

☎ Tel: (516) 632-8231
Fax: (516) 632-8240

Dr. Susan Solomon
NOAA Aeronomy Laboratory
325 S. Broadway
Boulder, CO 80303

☎ Tel: 303 497-3483
Fax: 303 497-5373

Dr. J. Staehelin
Atmospheric Physics
ETH-Honggerberg
8093 ZURICH
Switzerland

☎ Tel: (01) 377 2748

Dr. Knut Stamnes
Geophysical Institute
University of Alaska
Fairbanks, AK 99775-0800

☎

Dr. Leopoldo Stefanutti
I.R.O.E. of CNR
via Panciatichi 64
50127
FLORENCE, Italy

☎ Tel: 39 55 437.8512
Fax: 39 55 410.893

Dr. Daan P.J. Swart
RIVM Air Research Laboratory
P.O. Box 1
3720 BA BILTHOVEN
The Netherlands

☎ Tel: 31 307 42677
Fax: 31 307 42971

Dr. Nien Dak Sze
AER Inc.
840 Memorial Drive
Cambridge, MA 02139

☎ Tel: (617) 547-6207

Dr. George Tiao
University of Chicago
Graduate School of Business
1101 East 58th Street
Chicago, IL 60637

☎ Tel: (312) 702-7970
Fax: (312) 702-0458

Dr. Geoffrey Toon
JPL, Caltech
Mail Stop 183-401
4800 Oak Grove Dr.
Pasadena, CA 91109

☎

Dr. Peter Usher
UNEP - P. O. Box 30552
U. N. Headquarters Gigiri
Nairobi, KENYA

☎ Tel: 254-2-333930
FAX: 254-2-520711

Dr. Heikki Valmu
Helsinki University of Technology
Radio Laboratory
Otakaari 5A
02150 ESPOO
Finland
☎ Tel: 358 04512256
Fax: 358 0460224

Dr. Guido Visconti
Dipartimento Di Fisica
Universita' dell 'Aquila
Via Vetoio
67010 COPPITO (L'Aquila)
Italy
☎ Tel: 0862 4330755
Fax: 0862 453033

Mr. David A. Warrilow
Room B354, Global Atmosphere Division
Department of Environment
Romney House
43 Marsham Street
LONDON SW1P 3PY UK
☎ Tel: 01 276.8313
Fax: 01 276.8501

Dr. Robert Watson
NASA Headquarters
Code EEU
Washington, D. C. 20546

☎ Tel: (202) 453-1681
Fax: (202) 755-2552

Dr. Peter T. Woods
Quantum Meteorology Division
National Physical Laboratory
Queens Road
TEDDINGTON TW11 OLW, UK

☎ Tel: 01 977.3222
Fax: 01 943.2155

Dr. Robert de Zafra
State University of New York
Physics Dept.
Stony Brook, NY 11794

☎ Tel: (516) 632-8137
Fax: (516) 632-8080

Dr. Rudi Zander
Universite de Liege
5, Avenue de Cointe
4200 Ougree-Liege Belgium

☎

NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

DEC 19 1990

Honorable Robert A. Roe
Chairman
Committee on Science, Space
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Pursuant to Congressional direction contained in H.R. 3729, the "National Aeronautics and Space Administration Multiyear Authorization Act of 1989," as passed by the House on November 20, 1989, I am forwarding a copy of "NASA's Life Sciences Strategy to Enable Extended Duration Human Space Flight."

H.R. 3729 directed that NASA undertake a detailed study of the life sciences knowledge base requirements for Space Station Freedom and future manned space flight. Because this report was completed prior to final action on the FY 1991 VA-HUD-Independent Agencies appropriations act (P.L. 101-507), the program outlined reflects the President's FY 1991 budget request. This plan will be modified, as appropriate, upon completion of NASA's restructuring assessment of the Space Station Freedom program, currently under way pursuant to provisions of P.L. 101-507.

Sincerely,

Richard H. Truly
Administrator

Enclosure

cc:
Honorable Robert Walker

NASA LIFE SCIENCES STRATEGY TO ENABLE EXTENDED DURATION HUMAN SPACE FLIGHT

SUBMITTED TO:

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
UNITED STATES HOUSE OF REPRESENTATIVES

AND

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION
UNITED STATES SENATE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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DECEMBER 1990

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INTRODUCTION

This report is submitted in response to direction from the House Committee on Science, Space, and Technology, in Report 101-226, Section 20, August 31, 1989. The Committee directs NASA to undertake a detailed study of life sciences knowledge base requirements for Space Station Freedom and future manned space flight. Specifically, NASA is directed to:

"1. Review currently proposed manned space flight missions in order to:

(A) identify the physiological and other human factors knowledge base necessary to determine the human capacity to adapt to and perform effectively in the space environment according to mission requirements, including identifying which life sciences parameters must be measured and which technologies, processes and procedures must be developed; and

(B) develop a schedule indicating when specific components of information, technologies, processes or procedures identified under subparagraph (A) will need to be acquired or developed in order to verify that human adaptability requirements for manned space flight missions can be achieved.

2. Develop a strategic plan for life sciences research and technology development sufficient to accomplish the life sciences knowledge plan acquisition schedule developed under paragraph 1 (B), including--

(A) a crew certification plan setting acceptable crew deconditioning standards for Extended Duration Orbiter operations and verifying countermeasures sufficient to meet those standards before actual Extended Duration Orbiter operations; and

(B) a life sciences strategic implementation plan for the design and development of the Space Station, to be provided as part of the Preliminary Design Review for the Space Station, and to include crew adaptability standards; and

3. Verify the physiological and technical feasibility of the life sciences implementation plan developed under 2 (B), as part of the Critical Design Review for the Space Station."

This report outlines the NASA strategy in the medical and life support areas. It highlights requirements for assuring human health, safety, and productivity on missions of variable lengths. The report describes the evolution and status of the life sciences knowledge and supporting technology base, and defines what is to be learned from the Space Shuttle/Spacelab and Space Station Freedom programs. Finally, it provides proposed schedules for acquiring future life sciences data.

I. NASA STRATEGY FOR LIFE SCIENCES IMPLEMENTATION

In his July 20, 1989 speech commemorating the 20th anniversary of the Apollo 11 lunar landing, President Bush set out a clear long-term goal for the U.S. space program, beginning with the building of Space Station Freedom and then returning to the Moon to stay and proceeding with human exploration of Mars.

In fulfillment of this direction, NASA is: (1) identifying the requirements for research and technology development; (2) defining schedules for accomplishing the enabling research to understand the risks and to mitigate them; and (3) providing timely inputs into mission design and execution.

The following represents the major elements of the supporting research and technology base in the life sciences:

1. Focused and enhanced ground-based research in the areas of advanced low-gravity countermeasures; intravehicular and extravehicular life support; radiation and environmental health; human factors; artificial gravity countermeasure needs; and medical care systems.

2. Space Shuttle investigations to validate ground-based models, medical care procedures, and technologies through a series of dedicated Spacelab missions. The Extended Duration Orbiter Medical Program (EDOMP) will develop medical countermeasures for missions of 16 days and longer. The knowledge acquired as a result of these activities will feed into the overall database to support more advanced missions on Space Station Freedom.

3. Space Station Freedom investigations to play a pivotal role in understanding how to provide long-term support to space crews. The Freedom station will serve as a testbed: to verify low-gravity, individually tailored countermeasures to maintain crew health and productivity; to demonstrate the ability of life support systems to function with minimal maintenance or resupply; and to conduct controlled experiments utilizing the centrifuge facility for understanding the body's capability for recovery after injury.

4. The Space Exploration Initiative (SEI) poses an enormous challenge to the life sciences/life support programs. The elements described above are essential precursors to the SEI undertaking. In addition, an integrated ground and flight program that addresses radiation health risks is critical. Advanced life support concepts, including both physical-chemical and bioregenerative systems, must be validated and tested. Human factors and extravehicular activity technology for planetary surface operations are also important tasks. The Exploration Technology Program (ETP) will provide a major investment in research and technology development for the SEI.

Human missions beyond low-Earth orbit pose an enormous challenge to life sciences. While the elements of the programs described above are essential precursors to any such undertaking, two additional major issues also must be addressed. First, the radiation environment outside the protective shield of the Earth's magnetic field is far more hostile than that encountered in low Earth orbit. An integrated ground and flight program that addresses radiation health risks, solar flare warning systems, and new shielding technology is a necessity. Second, advanced life support that provides for closure of air, water and food production based upon integrated biological and physical-chemical systems must be validated on the ground first, and then tested on the Freedom station. More efficient and comfortable space suits for planetary surfaces will be developed and tested on Space Station Freedom.

Four overarching activities must be undertaken in order to assure a vigorous and viable life sciences program in support of manned missions:

1. Maintain and expand the unique space research facilities located at NASA's field centers, universities, and industrial centers;
2. Assure timely and sustained access to space flight to conduct critical experiments;
3. Coordinate research programs of national and international organizations to support space activities; and
4. Develop and maintain a unique national database consisting of life sciences information and the result of biomedical studies of astronauts conducted on a longitudinal basis.

The current strategy adopted by NASA is a multi-phased approach:

1. Maintain the core flight and ground research and development programs, and enhance their scope to support the future needs by the following actions:
   - enhance support to the NASA centers' unique facilities and talents;
   - establish NASA Specialized Centers of Research and Training at universities;
   - develop research programs to determine requirements for advanced technology as part of the Exploration Technology Program.
2. Develop and emplace an appropriate in-space infrastructure evolving from Space Station Freedom, and conduct critical research for advanced missions with humans;
3. Coordinate space exploration activities with other federal agencies and international partners.

Since 1970, the direction of NASA life sciences medical programs has evolved from operational support to seeking an understanding of the causative mechanisms underlying physiological adaptation in space. This knowledge is used to predict health-threatening issues and risks, develop more effective physiological monitoring capabilities, and devise countermeasures for maintaining crew health and productivity. The associated technology base encompasses life support systems, technology to aid and enhance human performance, and technology in support of extravehicular activities.

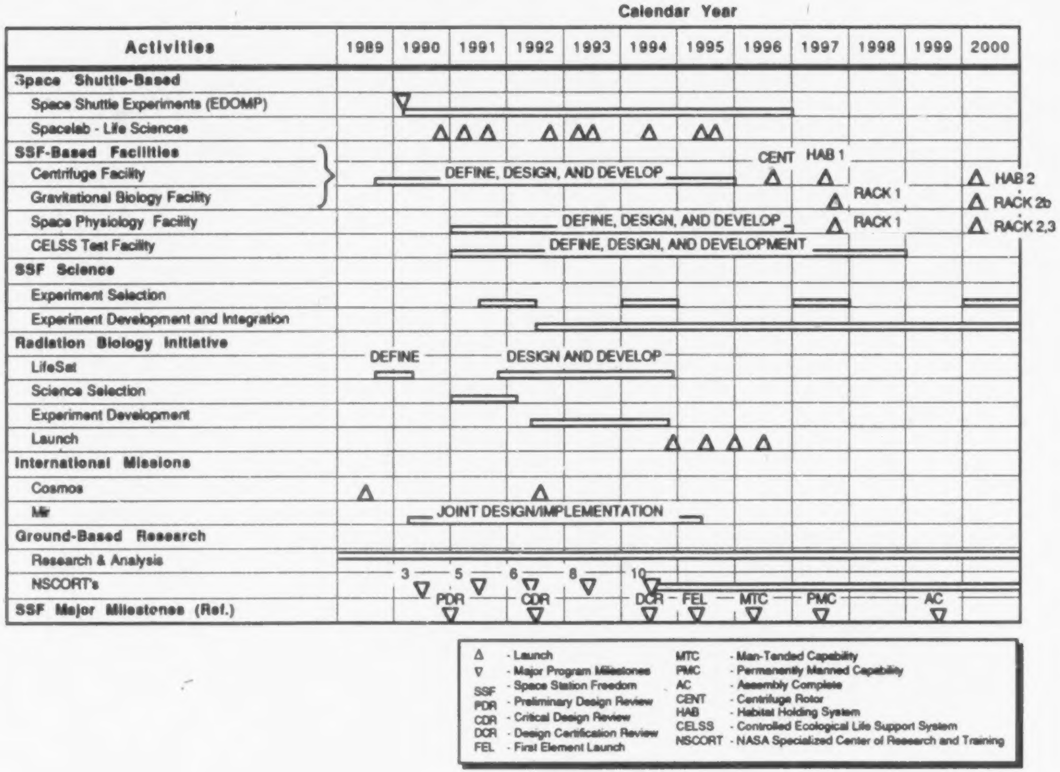
The NASA life sciences program is guided by two principal themes:

THEME I	**Ensure the health, safety, and productivity of humans in space**
THEME II	**Acquire fundamental scientific knowledge in space life sciences**

The two themes are interactive and have been carefully balanced. The first is mandatory in the support of overall national human space flight goals, while the second is both supportive of the first and an inherent part of NASA's space science and technology strategy. The sequence, pace, and schedules for implementation of the life sciences program strategy are based upon the overall goals of the National Space Policy.

The NASA comprehensive program strategy to provide the range of medical and life support capabilities necessary to the dynamic space missions envisioned for the next few decades is described in the following sections. Planning schedules for the overall program implementation, keyed to major flight programs, are shown in Figure 1.

Figure 1
Science Implementation



II. THEME I — ENSURE HUMAN HEALTH, SAFETY, AND PRODUCTIVITY

The health, safety, and productivity of crews on missions of any duration depend upon the provision of appropriate medical and life support systems that are matched to the mission objectives.

Fundamental differences between space and Earth — the reduction of gravity loading, confined environments, and radiation — challenge space life scientists and engineers to provide solutions and strategies to protect the health of crewmembers and enable productive operations. Major medical support and environmental health issues being addressed by this strategy are presented below. Each of the areas under consideration can have an operational impact on crew health, productivity and mission success. Overall synergism between these issues is not well understood at this time. Current countermeasures are directed toward each system separately; recently we have begun integrated ground and flight experimentation to investigate more advanced types of countermeasures which could be used simultaneously and more efficiently. The target dates for initial validation of these new countermeasures are included below.

MEDICAL SUPPORT ISSUES

ITEM	Major Findings	Clinical/Operational Impact	Understanding Mechanisms	Initial Countermeasure
Cardiovascular	Fluid loss Electrolyte changes Electrical activity disturbances Neuroreflex readjustment	Orthostatic intolerance	1994	1996
Neurovestibular	Motion sickness Gait disturbances Motor performance	Decreased productivity	1996	1998
Musculoskeletal	Bone mass loss Muscle mass loss	Renal stones Muscle/joint injuries Bone fractures	1999	>2000
Immunology/ Endocrinology	Changes in immune response Inappropriate hormonal metabolism	Susceptibility to infection Synergistic radiation effect Allergic reactions Acute metabolic disorders	2002	>2005
Medical Care	Infections Injuries Renal stones	Incapacitation	2000	2005
Human Factors	Early task performance impaired 1-g design incompatible with 0-g function	Low productivity	ongoing	>2000

ENVIRONMENTAL HEALTH ISSUES

ITEM	Major Findings	Clinical/Operational Impacts	Understanding Mechanisms	Technology / Countermeasure
Radiation	Chronic exposure limits exceeded Major solar flare hazard Potential 0-g synergy	Elevated cancer risk Death	2000	>2000
Intravehicular Life Support	Resupply of consumables Storage of consumables Toxicological events	Mission termination Volume limitation Crew performance degradation and/or illness	2004	2008
EVA Atmospheric Composition	Differences between cabin and suit atmospheres	Extensive pre-breathe periods Increased risk of bends	1991	1997
EVA Life Support	Limitations on workload capacity Limitations on portability	Low productivity	1996 (monitoring)	2008

The following sections describe the knowledge base status and future requirements in these areas. The requirements are derived from experience in early space flights, which ranged from 1 to 84 days. Longer duration missions on the Space Station Freedom and future human exploration ventures are likely to have similar, but more extensive requirements.

A. MEDICAL SUPPORT

Medical support systems will be required to provide: 1) countermeasures to potentially pathological changes produced by reduced gravity inflight or during postflight readaptation; 2) protection of crewmembers from unacceptable levels of space ionizing radiation; 3) optimization of habitability and human performance; and, 4) appropriate medical care for crewmembers.

1. Reduced Gravity Countermeasures

Introduction

Humans have successfully lived and worked in the weightless environment of space — occasionally for lengthy periods of time. Through observation, data collection, and subjective accounts, we have learned that physiological changes occur that may reduce performance in flight and impair the ability to readapt to a gravitational environment. It should be noted that these data have been collected while countermeasures were in use. Little information exists from only a few individuals who did not use countermeasures or used them only in a partial way. One of the conclusions which can be made from these observations, however, is that the current generation of countermeasures is only partially effective. Table 1 lists some of the known responses of physiological systems to space flight.

Table 1
What We Know

- Bone density is reduced.
- Muscle strength and mass are reduced.
- Neurological changes affect gait, stability, and cardiovascular function on return to gravity.
- Body fluid volume and blood volume, including red blood cells, are reduced.
- Orthostatic intolerance is experienced on re-exposure to gravity.
- Space motion sickness is experienced during the first week of space flight by about half of crewmembers.
- Cardiac arrhythmias are experienced during extravehicular activity.
- Immunity is impaired after prolonged space flight.
- Absorption of medications is impaired.
- Hormone blood levels and function are altered.

Background

Countermeasures to protect flight crews from the undesirable effects of space flight have been used on all space missions. Some countermeasures that address problems of short-duration flight are used as standard medical protocol during Space Shuttle flights of ten days or less. These include the consumption of salt and water prior to landing, the wearing of anti-g suits during landing to improve tolerance to orthostatic stress, and drugs and behavior modification to reduce space motion sickness. During longer flights, such as the U.S. Skylab missions and the Soviet missions on Salyut and Mir, exercise (often for several hours each day) has been used as a countermeasure to muscle atrophy and loss of exercise capacity. These countermeasures have partially reduced some symptoms during short flights. However, the longer missions planned for the future will require significant improvement in these countermeasures in terms of ease of use and efficacy.

Table 2 lists some of the relevant countermeasure questions which need further clarification and are now being addressed.

Table 2
Reduced Gravity Countermeasures
A Few Of The Relevant Questions To Be Answered

- What are the kinetics of bone loss during space flight?
- What is the time course of bone loss; is it a self-limiting function?
- How much bone loss can be tolerated and full recovery occur?
- Will the increased blood calcium cause kidney stones?
- What are the best countermeasures to bone loss?
- What cellular and biochemical changes occur within sedentary muscle?
- What is the best form of exercise to maintain adequate muscle mass?
- Does extravehicular activity after a period in weightlessness place inordinate stress on the heart?
- What combination of fluid loss, neurological and reflex changes, muscle loss, cardiovascular unresponsiveness, or other changes cause orthostatic intolerance?
- Are normal circadian rhythms disrupted in space without the normal light/dark cycle? What effect does this have on health and performance?
- Are cardiovascular, pulmonary, and other physiological responses to exercise different in weightlessness and reduced gravity; if so, what are the implications for work on the Moon and Mars and return to Earth?
- How much aerobic capacity should be maintained during space flight for extravehicular activity, work on the Moon and Mars, and return to gravity; and how should this be accomplished?
- Are neural communications disrupted in weightlessness, and, if so, how can they best be re-established?
- What immunological deficits result from prolonged stress and isolation?
- What impairments occur in absorption and metabolism of nutrients?
- What are the cumulative effects of repeated exposures to weightlessness?
- Are brief exposures to artificial gravity an appropriate countermeasure to physiological adaptation to space flight?
- Should a human centrifuge (artificial gravity) be included on a planetary vehicle?

Ground-based research utilizing recumbency (head-down tilt) provides a partial simulation of weightlessness for the purpose of studying fluid shifts, and bone and muscle changes. Other analogs are used to study different body systems. For example, the time course of bone loss has been studied in human subjects spending long periods at bedrest. Bone calcium loss and changes in bone density have been monitored, and potential countermeasures, including drugs, hormones, and exercise, have been investigated. Muscle tissue and strength loss have also been studied during bedrest and during flight. Various exercise protocols to counter such changes have been examined during bedrest. Electrical stimulation of muscle as an auxiliary countermeasure has also been examined. Fluid shifts and their effect on cardiovascular function have also been studied during relatively short (i.e., several hours to several days) periods of bedrest, as well as during periods that emulate actual space flights. Countermeasures such as fluid ingestion, lower-body negative pressure, and exercise are being tested to determine their effectiveness. Neurological changes, including those that seem to cause space motion sickness, have also been simulated on Earth. Sleds, spinning chairs, and other apparatus that stimulate the vestibular system have been used. A tilt/translational device, which simulates the conflict between tilting and forward movement that is experienced in space flight, is used to study neurological changes and may be used to preadapt astronauts to these changes.

Countermeasures Program

To develop an effective countermeasures program, we are implementing a carefully planned research program. It should be kept in mind that, so far, biomedical data on humans (especially on men for long-duration missions) has been collected while simultaneously utilizing countermeasures. We do not completely understand the full extent of the physiological changes that could occur without such countermeasures.

1. Better understanding of why the physiological changes occur requires systematic documentation of physiological changes and responses with and without countermeasures and for different age, sex and physical fitness groups. This is inherent in the Extended Duration Orbiter Medical (EDOMP) and Space Station Freedom Biomedical Monitoring and Countermeasures (BMAC) Programs.

The countermeasures currently used address the symptoms, not necessarily the causes. For example, consuming fluid and salt before landing is known to partially reduce orthostatic intolerance after space flight. But results of recent research indicate that changes in neural reflex function also occur. This knowledge may enable us to enhance the countermeasure to orthostatic intolerance — a problem that could impact the crew's ability to rapidly egress from the vehicle.

Continuation of our program of basic research on the ground, aboard the Shuttle, and later on Space Station Freedom is essential to validating optimal countermeasures developed and tested in ground-based laboratories.

2. Our findings will be tested using the EDOMP. The increased duration of Space Shuttle missions during the next few years will be both a challenge and an opportunity. The challenge is to prepare our crews to perform well in flight and readapt well to Earth. Because the crews are actively involved in landing the Space Shuttle, we must assure they have strength and coordination to successfully complete this task after these "Extended Duration Orbiter" (EDO) flights. Thus, we must immediately (during the present relatively short Space Shuttle flights) learn whether threatening changes can be expected to occur after 10 to 16 days and plan how to prevent them, especially during the entry and landing phases of the mission. Another challenge of the EDO flights is to be sure all crewmembers can safely egress unaided if an emergency landing is necessary. Thus, we must identify and develop countermeasures for losses of orthostatic tolerance, strength, and coordination that occur after 10 to 16 days of weightlessness.

The EDO missions will provide a key opportunity for obtaining data in a controlled fashion and validating the efficacy of new countermeasures for longer missions. A carefully designed and specifically targeted exercise program is an integral part of the countermeasure program for EDO.

3. In the late 1990's, countermeasures developed on the ground and verified during Shuttle/Spacelab missions will be tested on Space Station Freedom. The Biomedical Monitoring and Countermeasures (BMAC) Program is being developed to support these longer-duration tours of duty. This focussed program will validate the minimum set of critical physiological parameters to be routinely monitored and establish a range of medically acceptable risks. Table 3 lists proposed physiological parameters to be measured in space to enhance our understanding of adaptive physiological changes.

Table 3
Physiological Parameters To Be Measured In Space

- Body mass, size, and composition
- Body temperature
- Body movement
- Bone density
- Muscle strength
- Muscle mass
- Muscle electrical activity
- Electrolytes, hormones and volumes of fluid compartments
- Metabolic function
- Cardiac electrical activity
- Cardiac mechanical activity and chamber volumes
- Hemodynamics, including blood pressure and blood flow patterns
- Respiratory function
- Neurological function, including neurovestibular and cardiac reflex function and control
- Brain electrical activity
- Aerobic capacity (exercise)

The ultimate product will be a set of integrated countermeasure protocols, customized for individual variability within crews, that keep astronauts fit and healthy in weightlessness and minimize time for postflight rehabilitation. Freedom, in turn, will serve as a testbed for countermeasures designed to accommodate long stays on the lunar surface or interplanetary missions.

4. Determine whether some form of artificial gravity may be necessary to maintain muscle, bone, fluid, and neural integrity during interplanetary missions. A centrifuge can create forces similar to gravity; however, the centrifuge additionally creates coriolis forces that are unnatural. Thus, artificial gravity may reduce the negative effects of weightlessness, but it may create additional problems.

For the present, a dual-path program investigating means to provide artificial gravity and low gravity countermeasures has been proposed. Future transfer vehicles will likely be baselined for zero gravity, while investigations into the root causes of adaptive changes and the development of potential countermeasures will continue through ground-based and space research. Verification of the efficacy of countermeasures on Space Station Freedom should enable a decision on the need for artificial gravity around 2001.

2. Radiation Protection

Introduction

Protection from the hazards created by ionizing radiation in the space environment has been identified as a critical area for human exploration. At Space Station altitudes these hazards mainly result from particles in the trapped radiation belts. Outside of the Earth's magnetosphere the main radiation sources are protons from solar energetic particle (SEP) events and the highly charged, energetic (HZE) particles constituting galactic cosmic rays (GCR). Biological damage is produced by primary space radiation and also by secondary radiation resulting from the interaction of space radiation with the spacecraft structural materials. HZE particles (and, to some extent, protons and helium nuclei) can produce biological effects different from those produced by lightly ionizing radiation such as x-rays and gamma rays. For particles with different "relative biological effectiveness" (RBE), the same radiation dose can lead to widely different effects in different radiation fields.

Background

For low Earth orbit, a new set of radiation exposure limits was adopted by NASA in 1989. However, current knowledge is not adequate to predict the hazard to humans exposed to interplanetary radiation environments. The major sources of uncertainty are:

- SEP events, which are not currently predictable.
- Models based on a limited database used to describe radiation sources at different points in space and at different times in the solar cycle.
- The calculated transfer of radiation through shielding, spacecraft and tissue.
- The biological effects of HZE particles.
- The possibility that exposure to radiation in zero gravity produces more severe effects than exposure at 1 g.

The combined uncertainty for prediction of health risks has been estimated to be as large as a factor of 30 to 40, and it may not be possible to estimate the increased risk of cancer from radiation exposure during a particular mission. Attempts to compensate for the inadequacy of current knowledge by specifying worst-case shielding designs would lead to mass requirements that may exceed the capabilities of space transportation vehicles by as much as an order of magnitude.

Radiation Health Program

The strategy developed to deal with this problem consists of an expanded ground-based research program to build the required experimental database and theory, and use of a spacecraft for validation in the space radiation environment.

The objectives of the Radiation Health Program are: 1) to predict the probabilities associated with the biological effects of radiation (with particular emphasis on determining the chance of developing fatal cancers caused by HZE particles); 2) to reduce the cumulative uncertainty in the prediction of HZE effects to be within a factor of two by 1997 and lower than 25 percent by 2010; 3) to validate the ground-based results in space. These objectives are predicated on concurrent improvements in the characterization of GCR background flux (with 5 percent accuracy for HZE) and on the development of accurate, timely ground- and space-based solar monitors for prediction and warning of SPE. NASA will work with NOAA to develop this information.

The ground-based program currently relies on the Lawrence Berkeley Laboratory BEVALAC for beams of high-energy, heavy nuclei that simulate HZE radiation. This fundamental tool is used to evaluate both SEP and HZE particle effects. It is also important for calibrating space physics instrumentation, and for evaluating computational shielding methods.

Space-based radiation studies address four fundamental questions:

- How accurate are our predictions of radiation transport calculations?
- Are radiobiological models developed in ground-based studies valid models for predicting radiation risk in space?
- How do other space-related biological effects combine with radiation effects? In particular, are there synergisms between the effects of radiation and those of microgravity or other stresses?
- How should "dosimeters" be designed to predict the biological effects of HZE particles?

A program identified as LifeSat has been included in the Office of Space Science and Applications (OSSA) Strategic Plan since 1988, and has been targeted for a FY 1992 start. It encompasses the Radiation Biology Initiative leading to the expanded program outlined above. LifeSat will be a reusable, free-flying satellite that will provide access to polar orbits, both circular and eccentric, exposing biological samples to a significant amount of GCR. LifeSat will be capable of extended flights of 60 days or more. Two payloads can be carried, taking control samples to minimum-radiation orbits while other samples are exposed simultaneously to controlled amounts of space radiation. Studies of the combined effects of radiation and varying gravitational levels will also be performed. LifeSat will be used to validate *in situ* the data obtained from ground-based experiments.

3. Human Factors

Introduction

The human element is crucial in all phases of mission and system design and operation. Human factors is a multifaceted research area that ultimately seeks to identify and optimize those factors that influence crew behavior and performance. Table 4 shows some of the space flight factors addressed, along with proposed measures that can be implemented to ensure crewmember safety, well-being, productivity, and mission success.

Background

During the early days of the U.S. manned space flight program, the primary life sciences concerns focused on meeting the physical needs of the astronauts. In contrast, relatively little attention was paid to behavioral adaptation to reduced gravity or on crews' psychological or social adjustment to space flight. As space flight mission durations increased, especially with Skylab, more emphasis was placed on human factors concerns, although the emphasis was still limited to the study of spacecraft habitability.

An extensive and comprehensive core of ground-based and aviation-based research and technology in human factors is available. However, specific applied, operational and ground-based data must be developed and validated for the space flight environment. People undergoing long-duration stays in isolated, confined and potentially dangerous environments analogous to space have demonstrated

Table 4

Some Factors That Influence Behavior and Performance of Space Crews and Other Operational Personnel

Psychological, Social and Physiological Factors	Environmental Factors	System Design and Operation	Protective Measures for the human Operator
Psychological	Spacecraft habitability	Mission duration and complexity	Training
Limits of performance	Confinement	Organization for command and control	Preflight environmental adaptation training
Cognitive abilities	Weightlessness	Crew performance requirements	Social sensitivity training
Decision-making	Lack of privacy	Division of work:man/machine	Training for team effort
Motivation	Artificial life support	Information load	Cross training
Attitudes	Noise	Task load/speed	Inflight maintenance of proficiency
Emotions/mood	Work-rest cycles	Crew composition	Self-control training
Psychological stability	Shift changes	Space crew autonomy	
Personality variables	Desynchronization	Physical confort/quality of life	Selection
Human reliability (error rate)	Simultaneous and/or sequential multiple stresses	Communications (intra-crew and space-ground)	Selection criteria
Productivity	Hazards	Competency requirements	
Adaptability	Boredom	Time compression	Protection/support
Time compression	Physical isolation		Inflight psychosocial support
	Social isolation		Work-rest/avoiding excess workloads
Social			Ground contacts
Leadership			Job rotation
Crew composition			Job enrichment
Social skills			Recreation
			Exercise
Physiological			Recognition, awards, benefits
Space adaptation syndrome			
Spatial illusions			
Fatigue (physical and mental)			

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* Adapted from Research Opportunities in Human Behavior and Performance, Ed:J.M. Christensen and J.M. Talbot, NASA Contractor Report 3886, 1985.

non-adaptive behavioral effects. In environments such as undersea habitats, submarines, and polar stations in the Antarctic, low morale, heightened anxiety, sleep disturbances, fatigue, and even hostility have surfaced among highly trained and motivated crews. Such stress markedly reduces effectiveness and productivity. The Soviet program indicates that productivity and performance decrease on long-duration missions. Table 5 summarizes the long-duration Soviet manned space flight experience. Soviet life scientists have observed that advances in human factors will be a greater challenge to the success of missions longer than six months than challenges in any other area.

Table 5
Summary Of
Soviet Space Flights
Longer Than Two Weeks

MISSION DURATION	NUMBER OF MISSIONS	NUMBER OF COSMONAUTS	NUMBER OF COSMONAUTS ON REPEAT FLIGHTS
> 2 WEEKS	23	39	11
> 100 DAYS	13	24	5
180-184 DAYS	2	4	0
211-240 DAYS	3	6	0
326 DAYS	1	1	0
366 DAYS	1	2	0

Space Human Factors Program

NASA's missions and programmatic requirements involve understanding the underlying parameters of behavioral adaptation to, and human dynamics in, the space environment. Research activities in this field include determining the specific behavioral responses to exposure to microgravity, the dynamics involved in living and working in a small, enclosed space, and how these factors should influence operational and design requirements of the spacecraft.

NASA's approach uses both space experience and ground-based analogs to study behavioral, psychological, mental and physical performance responses. The approach involves understanding the time course and magnitude of the changes that occur; identifying the salient, critical factors and their underlying mechanisms of action; and developing standards, requirements, protocols, and effective countermeasures.

Analog facilities in remote, harsh environments on the ground can be used to develop crew selection criteria and training procedures, and to investigate small-group dynamics and habitat design. Antarctic expeditions and undersea experiences provide analog opportunities for human factors investigations. These, however, lack certain attributes unique to space exploration — prolonged isolation and confinement, limited rescue capability, the danger of radiation, and the reduced gravity that affects all day-to-day activities and threatens physiological and psychological well-being. Also, future space crews will have to work in spacecraft, in surface habitats, and on EVA excursions in situations where human error could have catastrophic or fatal consequences.

Research on the Space Shuttle will be essential in creating the knowledge base in space human factors. The EDOMP and research on Spacelab missions (IML-1, SLS-2 and IML-2) are designed to provide valuable data on physical and mental performance, and on sleep function and other physiological factors that can impact performance.

Space Station Freedom will provide an operational testbed to refine and verify procedures and systems, specifically testing the interaction of human factors in a hypogravity environment during longer duration missions. Knowledge gained in crew selection, training, and mission operations on Freedom will be applied to the planning for subsequent missions of greater duration and complexity.

4. Medical Care and Mission Support

Introduction

Providing medical care in remote or hazardous environments has traditionally been focused on stabilization of serious illness/injury, followed by transport to a definitive care facility. While analogous operations (e.g., submarines) provide some insight, certain factors unique to microgravity make health care in space a demanding challenge. Examples of these considerations include:

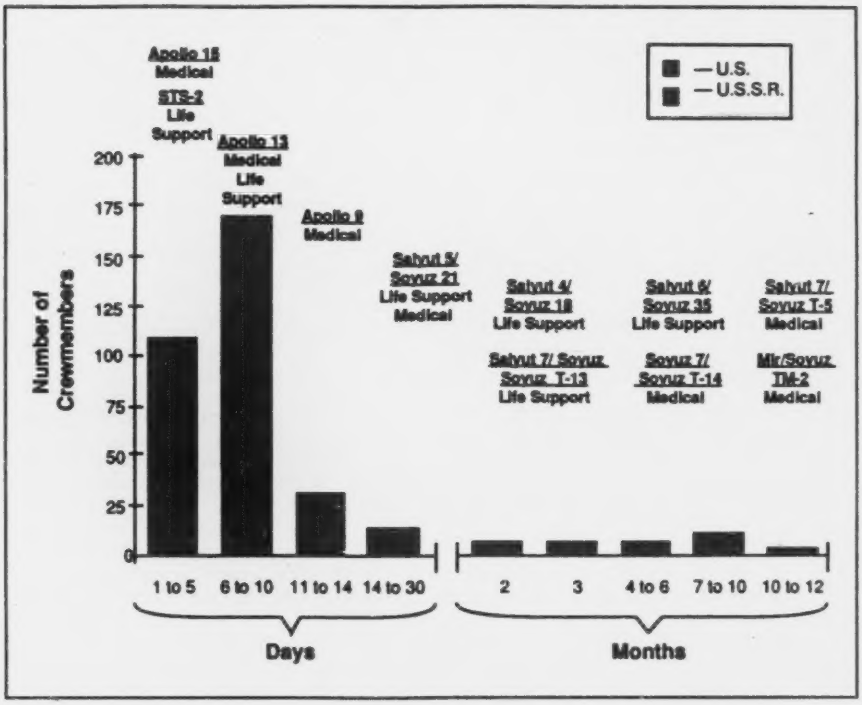
- Detrimental effects of microgravity on human physiology. There are two categories of responses to space flight: 1) Adaptive, such as cardiovascular, neurosensory, and hematologic changes, which do not present a significant health hazard until exposure to a gravity field; and 2) Pathological changes in bone, muscle, kidney, and immune systems which could result in either life-threatening or permanent health problems.

- Confined and remote operational environment.

- Medical procedures and hardware that require modification for use in microgravity.

- Advanced, "state of the art" life support systems, in which failures may result in medical consequences. Figure 2 lists serious medical and life support events that have resulted in mission abort or significant mission replanning. It should be noted that there is an increasing trend for such events with increasing mission duration.

Figure 2
Medical and Life Support Events In Space Flight



The design of medical care systems for space operations must consider these unique factors, as well as the following:

- Probability of medical illness/injury as a consequence of exposure to microgravity. The probability will dictate not only the monitoring and the preventive measures to reduce risk, but also the type of medical/surgical capability required for a given mission.
- Nature of mission (crew size, crew stay times, planned EVA or other operational considerations).
- Consequence and cost of a medical rescue or mission abort.

Background

The Space Shuttle is characterized by short missions with the capability for an emergency return to Earth and therefore requires a modest medical care capability. Space Station Freedom (SSF) and future exploration missions will be characterized by increasingly complex missions, longer stay times, and larger crews. In the case of planetary missions, spacecraft will use trajectories that preclude a mission abort. These considerations will mandate compact, efficient medical care systems capable of functioning in a progressively autonomous fashion.

Medical Care and Mission Support on Space Station Freedom

The Crew Health Care System (CHeCS) will provide for SSF operational needs during the first 5-10 years of permanent manned capability if no planetary missions are conducted. CHeCS will be fully operational by PMC. The subsystems of CHeCS are as follows:

- Health Maintenance Facility (HMF) — Includes diagnostic and therapeutic equipment, supplies, pharmaceuticals and a medical information management system. Provides in-flight medical support for injured or ill crewmembers, with capability to provide both ambulatory and in patient treatment. The design emphasis is on automation of data acquisition and analysis.

- Exercise Countermeasure Facility (ECF) — Provides equipment and techniques for exercise by crewmembers to prevent the physical deconditioning that occurs in space. The ECF will accommodate two crewmembers exercising simultaneously.

- Environmental Health System (EHS) — Provides equipment and supplies for environmental health assessments. It includes sampling, processing, and analysis of air, water, internal surfaces, and internal and external radiation environments.

As a supporting facility to CHeCS, a hyperbaric capable airlock will be provided. This is necessary for treatment of decompression sickness (bends), which could occur during EVA operations.

In addition to these provisions, studies to define an Assured Crew Return Vehicle (ACRV) are underway. This vehicle will function as a "life boat" or as a crew return vehicle if required. CHeCS will support the ACRV by stabilizing a patient prior to transport. ACRV will allow terrestrial treatment at appropriate hospitals for serious injuries or illnesses that could not be adequately cared for at the SSF medical facilities.

Exploration missions will require medical care systems that are capable of functioning in a completely autonomous manner, given that medical rescue would not be feasible due to the distances involved. These advanced systems will build on operational experience accumulated during the SSF program and will be configured to provide a wide range of clinical services in a "stand alone" mode or with telemedicine augmentation.

Key enhancements to the medical care capability that will be driven by this fact include:

- Major surgery capability
- Inpatient care for at least two patients
- Enhanced microbiological and toxicological diagnostic capability to monitor health of crew and environment (due to closure of air/water loops in life support systems)
- Comprehensive clinical diagnostic capability
- Proven exercise prescription and/or use of artificial gravity to prevent physical deconditioning
- Psychological health support system
- Increased telemedicine and automation capability
- Treatment facility for bends (hyperbaric chamber)

Research and technology development is also required in other areas unique to space medicine, such as extending the shelf-life of certain drugs and blood products and developing the means of administering them in a remote space setting. One unique issue related to medical care on certain planetary surfaces is that the surface materials themselves may present a health hazard to the crew. Analysis for toxic substances, and any potential biohazard, must be completed prior to landing the first humans on the surface. A sample return mission will be used to address this issue. The capability to protect the crew from exposure to potential pathogens on the planetary surfaces and upon return to the Earth is required. Facilities must be provided to rehabilitate crewmembers after return from extended missions.

The strategy for the enabling medical care research program is twofold: (1) build upon current and planned capabilities using the Shuttle and Space Station Freedom as operational testbeds to determine enhanced capabilities for future missions; and (2) design and develop appropriate Health Maintenance Facility analog testbeds at major medical centers to validate advanced technologies, train crews, and provide an Earth-based reference for telemedicine support. In addition, computer-aided diagnostic and therapeutic capabilities must be developed for use in telemedicine support.

Summary medical support schedules, keyed to SSF milestones, are shown in Figure 3, and the near-term flight mission plan to acquire the necessary data for life sciences research and technology development is shown in Figure 4.

B. CREW SELECTION / RETENTION STANDARDS AND PROCEDURES

Astronaut selections through 1969 were based on a ranking system, with no specific set of standards used for the medical selection. In January 1977 NASA published Medical Evaluation and Standards for Astronaut Selection: NASA Class I Pilot Astronaut and NASA Class II Mission Specialist. The procedures to conduct the medical evaluations were also stipulated. Two medicine boards were established. The Aerospace Medicine Board, at the Johnson Space Center, is responsible for the implementation of the standards while the Medicine Policy Board, at NASA Headquarters, is charged with the periodic review of policies and procedures. A longitudinal study of health indices of flight crew with matched control populations was instituted in 1977.

Figure 3
Medical Support

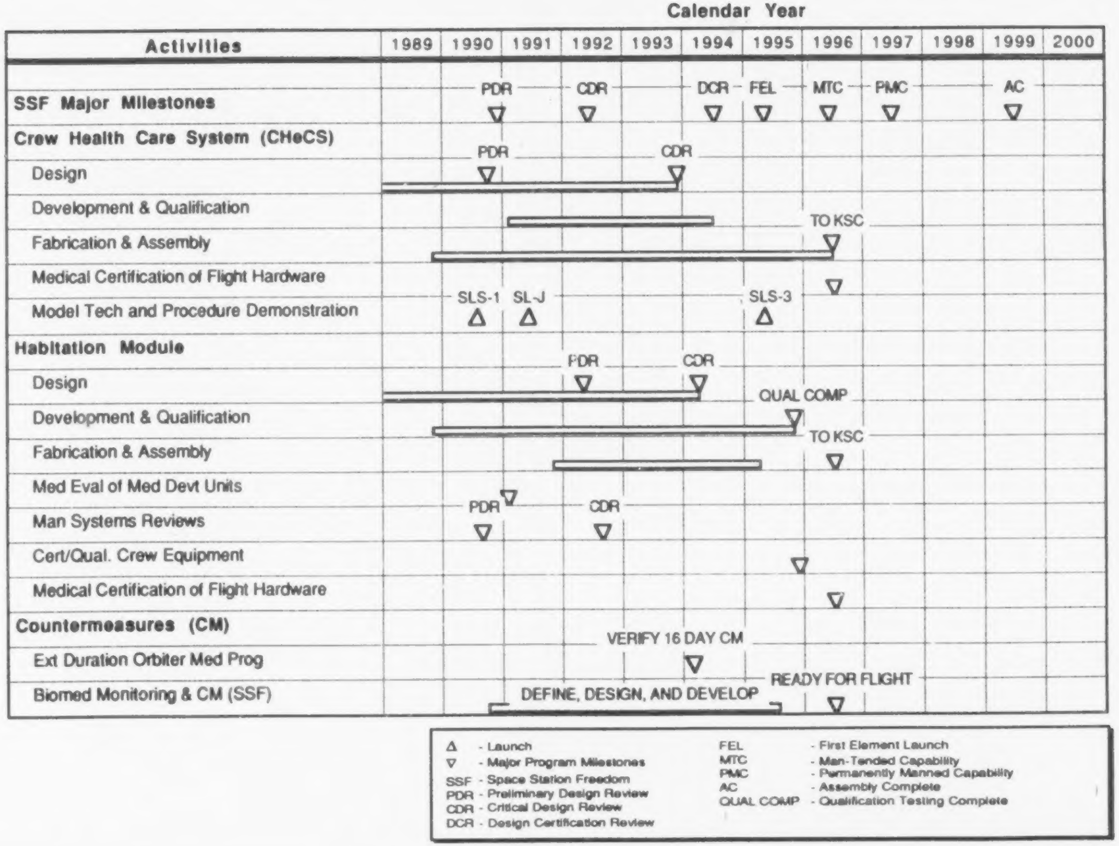


Figure 4
Near Term Flight Planning

DISCIPLINE	DESCRIPTION	SLS-1 (1991)	IML-1 (1991)	SL-J (1991)	SL-D2 (1992)	SLS-2 (1993)	IML-2 (1993)	SLS-3 (1995)	IML-3 (1995)	COSMOS (1992)	LIFESAT (1995)	Sec. PL (Periodic)
CARDIOVASCULAR	Cardiopulmonary, fluids, electrolytes	1	2		2	2	2	2	2			2
MUSCULOSKELETAL	Bone, calcium metabolism, muscle modification	2		2		1		1		2	2	2
NEUROVESTIBULAR	Neurophysiology, motion sickness, neurobiology	2	1	2		2						2
REGULATORY PHYSIOLOGY	Endocrinology, metabolism, immunology, pharmacology, renal physiology, rhythms	2				2		2	1			2
RADIATION	Radiation effects, exposure limits, shielding		2							2	1	
SPACE HUMAN FACTORS	Human-machine interactions psychology and group dynamics, performance		2			2	1	2	2			
LIFE SUPPORT	Plant physiology, EVA, bends, food and air quality, agriculture engineering	2				2						2
MEDICAL CARE TECHNOLOGY	Surgical workstation, health maintenance facility, diagnostics	2		2				2				

1: Primary Emphasis
2: Secondary Emphasis

In 1989 a Space Station Medical Standards Working Group (SSMWG) was set up at the Johnson Space Center. The objective was to produce a set of medical standards for all Space Station Freedom and Space Shuttle crewmembers. These standards are more focused in order to screen for medical problems that might impact operations on planned SSF missions of up to 180 days. Space flight research into potential risk factors is continuously fed into the process of establishing medical standards for selection. Research also contributes to the annual modification of risk factors in the general astronaut population.

C. LIFE SUPPORT

Introduction

As humans move away from the Earth, a major challenge is to provide a reliable, cost effective, life-sustaining environment in locations that are naturally devoid of food, air, and water. Life support systems must provide these commodities during all phases of human missions — during intravehicular activity (IVA) within space vehicles, in surface habitats and pressurized rovers, and during extravehicular activity (EVA).

The maintenance of a safe environment for human habitation goes beyond the minimum required to sustain life through the provision of adequate air, food, water, and waste handling systems. The habitable environment must permit the provision of appropriate medical monitoring and care, must be monitored for radiation exposure, and must provide shielding appropriate to mission operations. The habitable environment must be continuously monitored and controlled for the presence of toxoids, either microbial or chemical, as well as for appropriate temperature, humidity, and atmospheric composition. The buildup of undesirable substances in a tightly closed environment is a major design concern, and the control mechanisms must incorporate provisions for effective removal and simple routine maintenance.

Background

Requirements for life support beyond 10 days will be met next in the Space Shuttle Extended Duration Orbiter (EDO) program, and then for 90-180 days in the Space Station Freedom program. For missions beyond Space Station, new life support systems, human performance methods and models, and surface EVA technologies are planned for development as part of the NASA Exploration Technology Program. The EDO program will upgrade the capacity of current Shuttle systems in some areas, and provide a regenerable CO_2 removal capability reminiscent of Skylab, but the EDO will depend on the resupply of all life support consumables for its operation. For a system that is permanently stationed in space, however, operations will require reduced resupply requirements. Therefore, the Space Station Freedom (SSF) program will, to the extent possible, recycle life support consumables. The recycling systems to be used on SSF are based on technology that was developed for Skylab and part of NASA's life sciences research in the early 1980's. The design goal for SSF is to recycle or regenerate up to 95 percent of the air and water required by its crew, while resupplying food and removing waste materials to Earth. Technology selection and certification of SSF life support systems is being accomplished through testbed activities conducted at the Marshall Space Flight Center. Actual performance results and maintenance requirements will be determined as the program progresses into its operational phase.

Current intravehicular life support systems provide a habitable environment in space, but at great cost. The open-loop life support systems currently in use require that the air, food, and water be resupplied from Earth. These systems do not recycle the resulting waste products, which must be returned to Earth or left in space. Since each human requires approximately 6.5 kg of water, air, and food each day, provisions for a crew of four run to nearly 9,500 kg per year. In addition, if the crew is to bathe, wash dishes, flush toilets, and clean clothes, then the crew need expands to nearly 28,500 kg of provisions each year.

Future missions will pose requirements for life support systems to meet a variety of needs. For example, because of the additional cost of Earth-Moon transportation, as much as seven times the mass required on the lunar surface must be delivered to low Earth orbit prior to delivery to the Moon. Supplying the minimum set of life support consumables for one person, without hygiene and wash water, would require approximately one heavy lift launch vehicle every two years to low Earth orbit. This additional mass penalty makes it even more important to develop regenerative (i.e., recycling) life support systems to enable the exploration goals of permanent human presence and eventual self sufficiency. Therefore, technology advancements are needed to achieve the required capability using pure physical-chemical, pure bioregenerative, and hybrid approaches.

IVA systems will be required for planetary transfer vehicles, excursion vehicles, long-duration habitats, and pressurized rovers. EVA systems will have to be provided for planetary surfaces, and for space operations in orbit and in transit. Perhaps the most challenging set of systems will be those required for Mars exploration, where the Mars transfer vehicle must have a resupply-independent life support capability that will last as long as three years, and a Mars habitat that will support five people for up to 500 days.

Technology was developed for Apollo that allowed successful, short-term EVA on the lunar surface (1/6 of Earth gravity). For long stays on a planetary surface, however, current systems are inadequate for projected mission requirements. Apollo technology is not maintainable, and is too massive for use on Mars (2/5 of Earth gravity), while the Space Transportation System Extravehicular Mobility Units (EMUs) are designed for use in microgravity, and are even more massive.

To deal with the additional demands of the exploration opportunity, future surface EVA systems will include enhanced anthropomorphic suits similar to those now in use, but will also include new elements that blur the line between suits and habitats. Repeated, productive surface activity for eight hours each day for up to six days a week are projected future mission EVA requirements. Suits will have to be maintained by the crew, and must be resistant to contamination by planetary materials such as dust.

For both EVA and IVA systems, it will be critical that these functions be achieved with the provision of a safe, non-toxic environment, and with food and water supplies that are not only free of contamination, but provide adequate nutrition and psychological benefits.

A summary life support development schedule, keyed to Space Station Freedom milestones, is shown in Figure 5.

Intravehicular Activity (IVA) Life Support Program

IVA life support development strategy includes the following guidelines:

- Use closed-loop systems wherever practicable to reduce logistics requirements.
- Use open-loop systems wherever power, mass, volume, and operational requirements dictate, or where development timelines preclude the use of a closed-loop system.
- For habitats and long-duration vehicles, provide for life support system growth and evolution as technology progresses.

An example of the latter would be the initial establishment of a core physical-chemical system in a habitat that would be compatible with the later provision of plant-growth systems providing food as well as air and water to the habitat.

IVA life support systems must address the following major performance areas:

- Air Revitalization
- Water Reclamation and Purification
- Food Supply
- Waste Processing
- Environmental Monitoring
- System Control
- *In Situ* Resource Utilization
- Thermal and Humidity Control
- Fire Suppression
- Contamination Control
- Maintenance by the crew

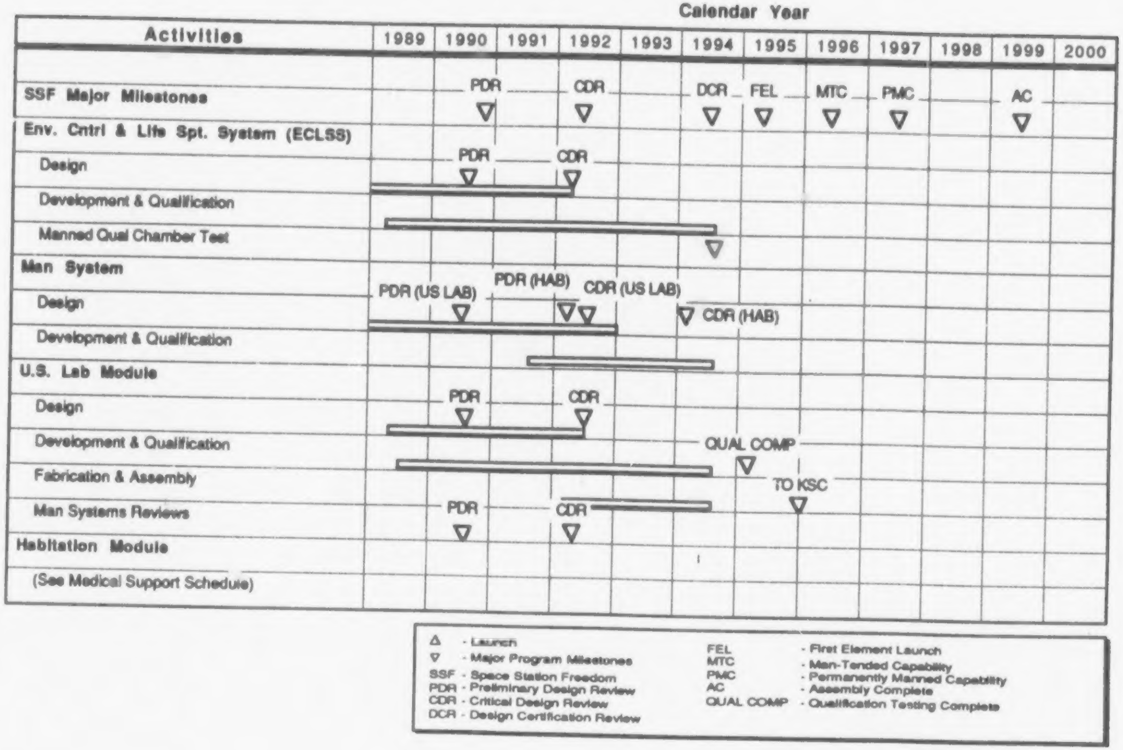
Life support systems to be developed for future missions fall into three basic groups:

- Short-term Transfer and Planetary Excursion Vehicles — Open systems are presently baselined for these vehicles because these applications are either near-term, precluding development of more closed systems, or are low-power systems where regenerative life support may not pay direct benefits. All of these applications have relatively short use times, with operational restrictions that allow the use of open life support. However, system studies are currently being conducted to determine open-vs-closed system advantages.

- Initial Surface Habitats and Planetary Transfer Vehicles — These applications are baselined to use physical-chemical regenerative systems as the basis for their design, with some fresh food supplementation. The life support systems may have significant Space Station Freedom heritage. Major enhancement of the Freedom systems will, however, be required. Such enhancements may also provide significant benefits back to the evolution of Space Station Freedom systems.

- Upgraded Planetary Habitats — These systems must meet the needs of applications where there are a number of people living for long periods. Minimizing resupply requirements to offload the logistics train and provide the basis for self-sufficiency is paramount. The development time-lines for these applications will allow the perfection and testing of hybrid physical-chemical and

Figure 5
Space Station Life Support



bioregenerative systems. Bioregenerative capability can be added to an enhanced-technology physical-chemical core system incrementally over time. The use of local resources will further reduce resupply.

In order to provide technologies for life support, the initiation of an intensive research and development program is needed. Regenerative life support systems are critical to the design and selection of future exploration missions, but they have yet to be tested with humans. Space Station Freedom is developing systems that will use recycling technology to supply a portion of the potable water and all of the hygiene and wash water for the crew. At a later date, regenerative oxygen revitalization and more complete drinking water recycling will be added. The research and development of these technologies need to be accelerated to meet future exploration mission needs. Such a program will utilize Space Station Freedom capabilities and introduce new technologies as appropriate (both physical-chemical and bioregenerative system concepts). This program will use breadboards, testbeds, and flight opportunities for proof-of-concept testing at the component and systems level. A range of facilities, from university and industry labs to functional human-rated simulators will be required, as will integration testbeds to demonstrate and validate the technologies at the system level.

Life Support Technology Development Strategy for Future Missions

The need for an improved life support system knowledge base is driven by: 1) recent Space Exploration Initiative studies which require the capability to evolve a lunar outpost to maximum self-sufficiency; and 2) the requirement for a highly reliable and readily maintainable life support system for a Mars mission. The exploration technology program will build upon Space Station life support technologies, if appropriate, as determined from systems analyses and technology trades which are currently being conducted. The design of life support systems for future outposts and planetary transfer vehicles will also incorporate experience gained from ground research in testbeds and analog facilities. These life support systems will provide for evolutionary improvements in capability. At each step, testbeds will be used to develop and integrate the new technologies.

The strategy for developing the life support base for exploration missions have several steps. First, the initial core physical-chemical regenerative life support system—closed except for food—will be developed. This system will integrate air, water, waste and thermal subsystems, and will have the ability to be monitored and controlled in real-time without the need for crew interaction and/or intervention. The core physical-chemical life support system will then evolve to include supplemental food growth and bioregenerative concepts for life support as these mature and are proven feasible. The final step will be the creation of a full bioregenerative life support capability that provides cultivated food as well as supplemental air, water and waste processing using a plant growth facility.

Extravehicular Activity (EVA) Life Support Program

EVA systems will have to provide the basis for much of the operational capability of the future exploration missions. Human interaction with planetary surfaces, the ability to construct and maintain space vehicles, and the emplacement of a surface infrastructure will depend on these systems. Whether provided by an EMU alone, or by more complex systems, there are a set of desirable features associated with EVA systems:

- Minimal transition time between IVA and EVA — Particularly important here is the difference between the habitat pressure and the pressure of the EVA system. The difference in pressures affects the likelihood that a crewmember will develop the bends, with a greater difference being less safe than a smaller one. Conversely, higher EVA pressures demand more robust EVA systems, and can limit the capability of systems because of higher mass requirements and limitations on glove flexibility at the higher pressures.

- Maximization of time available for productive EVA — If the EVA system depends on human power for mobility, then suit mass can be a limiting factor on EVA time. Portable life support system capacity and ease of recharging is another constraint. As EVA durations increase, the ability to supply food, remove wastes and provide "creature comforts" for the crewmember must be taken into account. Concerns about air and water quality and radiation protection also become more pronounced. Overall time for EVA on a mission is a function of the maintainability of the EVA system. Systems must be designed to reduce the need for extensive overhaul after use and for routine, *in situ* maintenance.

- Minimum restriction on normal human capabilities — Such constraints as suit mass and overall size can limit human capabilities in an EVA system. If humans are to routinely do hard work during EVA, then the full range of metabolic levels must be supported with adequate thermal control. Suit mobility in the area of gloves, the torso, and boots are important to overall productivity. Communications capability of the EVA system must support crewmember-crewmember and crewmember-habitat interactions for safety and productivity reasons.

Current capabilities in planetary surface EVA derive from Apollo with the benefit of Skylab/Shuttle experience, and provide an excellent starting point for future missions. The Apollo suit was a limited lifetime design, without maintenance and refurbishment provisions, and was affected by dust contamination. In addition, the low pressure suit design would prohibit use of higher-pressure/two-gas habitats, while the mass of that EMU would be too high for use on Mars. In the area of microgravity EVA, there have been significant advancements. Nevertheless, existing portable life support systems have reduced volumes from Apollo but are slightly heavier. The Space Shuttle EMU has proven durable and robust, and EVA capability between major ground checkouts has been extended to support Space Station operations. It is intended to provide all EVA support needed to assemble Space Station Freedom, and may provide all low Earth orbit EVA support for any future assembly of lunar and Mars transfer vehicles. Possible improvements include higher operating pressure to reduce prebreathing, regenerable CO_2 removal, and long-life batteries to reduce logistics and on-orbit maintenance.

Near-term, focused research and technology areas that must be emphasized include:

- Lightweight and durable materials
- Glove design
- Dust contamination protective measures and techniques
- Lower torso mobility systems for walking
- Ancillary mobility systems for surface transportation
- Lightweight, compact, regenerable and portable life support system technologies
- Information displays and control technologies
- Mobility aids

The in-space EVA needs of future exploration missions may be satisfied by the EVA systems evolved from the Space Shuttle program, but extensive research and development is required for planetary surface EVA systems. These needs should be met by parallel technology development within the Exploration Technology Program that will minimize the risks for surface EVA systems by providing lightweight, high pressure suit options. This would include mission-specific suit, portable life support, and mobility aids technologies.

III. THEME II — ACQUISITION OF FUNDAMENTAL KNOWLEDGE

The strategy for the acquisition of fundamental knowledge in life sciences must meet three challenges: (1) be responsive to the priorities of the communities it serves; (2) match the knowledge acquisition with the most appropriate mission implementation; and, (3) optimize the timely transfer of the knowledge into the life sciences community.

While basic research in the space life sciences is considered to be "an evolving science," it is firmly based upon a centuries-old tradition and knowledge base of ground-based data and experimental procedures. Since biological variability is a property of all living species, proper experimental design must include the use of statistically significant populations exposed to controlled alterations of the experimental variable. Independent replication of the experimental protocol on a subsequent set of subjects with comparable outcome is accepted as validation of the results.

The selection of appropriate experimental subjects must be based upon the ability of the species population to present a consistent response to the experimental challenges. Matched control populations in which the experimental variable either remains unaltered or is altered in a precisely regulated pattern serve to clearly distinguish confounding factors. While the human response to space flight exposure represents the subject of most interest to the designers and implementors of space missions, the human species is seldom the optimal experimental population in which to study responses of fundamental mechanisms to altered environmental variables such as reduced gravity.

This section presents the strategies for the acquisition of fundamental knowledge in the space life sciences needed to support the national space goals.

A. STRATEGY 1 — RESPOND TO COMMUNITY PRIORITIES

The space life sciences program must be responsive to two principal communities — the scientific community and the mission implementors. The latter group seeks basic scientific knowledge in specific disciplines to enable the development and implementation of efficacious mission capabilities for medical and life support elements. The scientific community seeks to utilize the space flight environment as an experimental tool with unique capabilities. A certain degree of commonality exists in the research priorities that have been established by both communities. A close working relationship is maintained with individual discipline working groups, composed of members from the scientific community, to ensure that the program elements are both responsive to the needs of the scientific community and appropriate for NASA implementation.

This continuing NASA life sciences assessment process has been periodically focused by external studies directed toward specific Agency objectives, evaluating the requisite knowledge base required by the objectives against the program's capability to produce this data in an integrated and timely manner. The National Research Council (NRC) 1979 Bricker Report provided focus for life sciences in support for and utilization of the Space Transportation System. Two subsequent NRC studies provided specific focus in 1987 for implementation of life sciences research on Space Station Freedom (the Goldberg Report) and enabling science and technology data sets required for future human exploration missions (the Shea Report). In 1988, another NRC study focused on future scientific endeavors for the decades between 1995 and 2015 (the Swisher/Usher Report). (Full citations are contained in the Appendix.)

Realizing the critical role assigned to NASA's life sciences programs in future Agency planning, the NASA Advisory Council commissioned the Life Sciences Strategic Planning Study Committee (LSSPSC) in 1986, and charged the committee with developing a comprehensive view of space program issues related to the life sciences, recommending goals for NASA's life sciences efforts, and devising feasible scientific and technical strategies to achieve these goals. The LSSPSC presented the results of its research, including findings, recommendations and a strategy for life sciences, in its 1988 report, "Exploring the Living Universe: A Strategy for Space Life Sciences".

The current NASA life sciences strategies and evolving programs have been shaped in response to the priorities and recommendations proposed by these communities.

B. STRATEGY 2 — MATCH SCIENCE WITH PLATFORM

This strategy is founded upon the need to assure timely and sustained access to space flight, thereby facilitating the conduct of critical life sciences experiments. Since each space flight mission offers a unique range of capabilities, this strategy seeks to optimize the scientific return by matching the mission opportunities to specific experimental requirements. The research requirements addressed in this strategy are: (1) the exposure of significant numbers of appropriate specimens; (2) controlled presentations of the experimental variable; and (3) a period of time that is significant for the experimental system.

When the experimental system requires humans as either the most appropriate specimen or as experiment executors, then the human space flight mission is the necessary platform. When the scientific requirements can best be achieved without direct human interaction, then the unmanned free flyer is the most appropriate platform. When the most appropriate setting is ground-based, the strategy focuses upon the use of university/industry facilities, unless NASA-unique capabilities are required.

The implementation of this strategy has resulted in the NASA life sciences programs developing flight experiments for unmanned COSMOS biosatellite missions, Space Shuttle middeck locker capabilities, and a variety of Spacelab missions, both dedicated to life sciences and in concert with other microgravity partners. The Spacelab missions now enable the performance of experiments that require 7 to 13 days of flight and human intervention on-orbit. A limited range of analytical capability is provided on these missions, with the primary objective being to perform observations and collect samples and specimens during flight for subsequent Earth-based analyses. The extension of Spacelab flights to periods of time beyond 13 days enables experiment replication on the same flight.

A reusable, free-flying biosatellite (LifeSat) that enables studies using living biological specimens including plants, rodents, cell and tissue cultures, and other small organisms is currently under consideration. In addition to retrievability, this biosatellite would have a unique set of technical capabilities, including access to orbits that the Space Shuttle cannot reach (e.g., polar orbit), extended flights (e.g., 30 to 60 days), and exposure to varying gravity levels (e.g., 0 to 1.5 g).

Space Station Freedom has great significance for NASA life sciences programs. For the first time it will enable the study of significant numbers of experimental specimens with appropriate controls and real-time analytical capabilities over an extended period of the subject's life-span. Freedom will provide the means to acquire fundamental knowledge both from the standpoint of basic scientific research and in enabling extended-duration exploration missions. The basic life sciences research strategy for the utilization of Space Station Freedom is a "single stream" pressurized laboratory approach. This means that there will be a transition from Space Shuttle/Spacelab to Freedom research as early as is feasible, and that once an outfitted Freedom is available, there will only be dedicated Spacelab flights when the science to be implemented can be best accomplished on such a mission. While there are no current plans for a dedicated Spacelab Life Sciences mission after SLS-3 (1995), evaluations will be made of the cost and feasibility of dual compatibility (Spacelab and Freedom) hardware to provide flexibility to accommodate schedule changes. Configuration and timing decisions will be in keeping with Freedom schedules.

The life sciences fundamental research programs on Freedom require a suite of integrated equipment that will provide generic laboratory capabilities for the program. Certain equipment, such as gloveboxes, refrigerators and freezers, will be provided by the Freedom program. Focused generic research facilities for gravitational biology, space physiology, exobiology and bioregenerative life support are being developed under the NASA Office of Space Science and Applications (OSSA) Space Biology Initiative.

The OSSA Centrifuge Facility for Space Station Freedom is expected to be the single most important research tool for space life sciences. This facility will provide controlled levels of artificial gravity for experiments using plant and small animal specimens in research designed to separate the effects of weightlessness from those of other environmental factors and to conduct controlled experiments on tissue regeneration in zero-g after injury. To date, only very small centrifuges (a fraction of a meter in diameter), accommodating only a limited range of specimens, have been flown on Space Shuttle/Spacelab missions and on Soviet biosatellites. The Centrifuge Facility will enable investigations on multiple specimen types over durations representing a significant portion of the life-span of the specimens. This research will greatly enhance our understanding of the mechanisms underlying the physiological and biochemical changes in humans and other living organisms that take place in the space environment.

The Centrifuge Facility will be able to produce a range of gravity levels from 0.01 to 2.0g. A minimum of two levels of biological isolation will be maintained at all times between research specimens and crewmembers. In addition, automated mass balancing and vibration isolation for the centrifuge rotor system will not permit the level of disturbance transmitted to habitats and other payloads on Freedom to exceed the specified microgravity environment required of the Space Station program.

C. STRATEGY 3 — TRANSFER KNOWLEDGE TO THE USERS

This strategy focuses upon three elements of the NASA life sciences program to meet its objectives: (1) an integrated community interface structure, involving discipline working groups (DWGs) and advisory committees; (2) the science recruitment and implementation system, involving close collaboration with the science community infrastructure including other government agencies; and, (3) the development of an active data archiving and retrieval system.

The current life sciences program supports working groups of scientific experts at each of the discipline levels. The DWGs are vertically integrated across internal and external advisory committees and contain members actively involved in the development of similar life sciences programs in other government agencies. Such cross-fertilization provides a continuing assessment of the scientific validity of the NASA life sciences programs, assists in defining scientific priorities, and establishes the appropriateness of NASA implementation of the science. The regular interactions of NASA program managers with each of these groups also provides an opportunity to disseminate the results of NASA research into the larger scientific community.

The science recruitment and implementation system developed to support NASA life sciences research is also an active disseminator of data acquired by both ground and space flight experiments. It is the expected norm that each investigation will culminate in the peer-reviewed publication of the results. In addition, the NASA life sciences programs actively promulgate focused collections of data on a regular basis. Focused workshops in evolving science areas provide a continuing series of status reports on the accumulation of knowledge and projections of future requirements. It is expected that this area of knowledge dissemination will rapidly increase as the NASA life sciences programs evolve into a more active flight status.

Finally, OSSA is defining a life sciences data archiving system to facilitate the orderly preservation and dissemination of integrated data sets and specimen samples. The archive system register, as currently envisioned, is planned to be accessible through a common network backbone providing controlled access to all investigators.

IV. EXTERNAL INTERFACES

A significant aspect of NASA's strategy to ensure the timely availability of scientific knowledge and technology to support extended duration human space flight is the use of an extensive array of external relationships.

The university community continues to offer a broad life sciences research and training base for OSSA. This diverse community is also the source of the majority of the members of our various discipline working groups and advisory elements. The initiation of the NASA Specialized Centers of Research and Training (NSCORT) program and the establishment of the first centers in the latter part of 1990 are highly significant steps in the strengthening of the university-based research in life sciences. As NASA's planning for long-duration missions matures and resources become available, university research will assume even greater importance in the overall approach to meeting the scientific and technical challenges presented.

Joint activities with other Federal agencies are essential to the continued development of a national life sciences program base. An Interagency Working Group (IAWG) in biomedical research consolidates and enhances joint efforts between NASA and the National Institutes of Health (NIH). Complementary ground-based research programs are being developed in the cardiopulmonary, musculoskeletal, and neuroscience disciplines. A similar cooperative program is planned with the Department of Defense (DOD). DOD has several life sciences research programs of interest. For example, the School of Aerospace Medicine conducts ongoing radiation research on the biological effects in mammals (i.e., rhesus monkeys) exposed to protons. This continuing research program was initiated in the 1960's and currently includes a longitudinal study of a rhesus monkey colony. The Armed Forces Radiobiology Research Institute (AFRRI) of the Defense Nuclear Agency supports a comprehensive biomedical research program on ionizing radiation. The purpose of the program is to develop medical treatments (i.e., radioprotectants) and performance measures required to support operations in a radiation environment. NASA and AFRRI expect to sign a memorandum of understanding (MOU) for collaborative activities this year. NASA-supported researchers currently utilize the Department of Energy (DOE) facilities for studying the effects of heavy ions on animals and measuring input fragmentation for updating transport codes. Relationships with other agencies are also being developed. These joint activities will ensure that ground-based and flight facilities, with the appropriate management and scientific infrastructure, are available to support the needs and interests of other agencies as well as those of NASA in the utilization of space as a scientific tool. Specific interests will be integrated to ensure the development and execution of ground and flight research programs that meet the needs of all participants.

NASA has been developing research and technology interchange programs with other relevant agencies in the area of medical and life support systems. The U.S. Navy, Army, and Air Force have participated in a life support conference sponsored by the NASA Office of Aeronautics, Exploration, and Technology (OAET) to exchange information on program objectives, and goals, and technical content which may have synergistic benefits. OAET and the Navy meet quarterly, explore areas of potential joint programs, including the potential use of a Navy submarine as a life support testbed. The Navy may also provide closed atmosphere samples to NASA as part of an OAET program to develop and validate expert systems for use with atmospheric measurement devices. Existing and planned R&D programs within the Army and Air Force will also be evaluated for their applicability to NASA's life support technology requirements.

OAET will also initiate discussions with the Environmental Protection Agency and the Department of Energy in the areas of toxic waste cleanup and sensing and monitoring technologies, which are being developed to address environmental issues on Earth and which may have direct applications to NASA's requirements for life support needs for exploration missions. The development of new life support technologies by OAET for the proposed exploration missions may also have direct or indirect terrestrial applications to address air pollution and water reclamation needs.

OSSA is continuing to pursue a vigorous international program involving the major space agencies of the world, especially in the training of life scientists. The goal of international cooperation in the life sciences is to increase the overall worldwide science return from space life sciences research. The strategy is to shape, with our international partners, mutual goals and objectives. In so doing, we jointly minimize duplication of efforts and technology development. To this end, the NASA Life Sciences Division has established formal collaborative relationships with Canada, the European Space Agency, the Federal Republic of Germany, France, Japan, and the U.S.S.R. In addition, discussions have been held with several other countries to determine the feasibility of establishing formal collaborative relationships.

V. SUMMARY

Development of life sciences knowledge, including understanding of human factors and development of appropriate medical and life support systems, is critical to any future human space exploration. The science and technology programs described in this document have been specifically designed to:

- Identify and reduce the medical and life support risks associated with near-term operations of the Shuttle through completion of the Extended Duration Orbiter Medical Program (EDOMP) by 1993.
- Develop requirements for medical and life support on Space Station Freedom. These requirements are being implemented for the assembly phase of Space Station Freedom in the component elements of the Crew Health Care System (CHeCS).
- Identify and reduce the medical and life support risks associated with continuing operations of the Space Station through the development and implementation of the Biomedical Monitoring and Countermeasures (BMAC) program by 1997.
- Define the medical and life support requirements necessary to support definition of evolving manned missions.

The integrated strategy detailed in this document is based on broadly based scientific advice, builds upon existing knowledge sets, and leads to the required database to support future mission planning. Successful implementation of this strategy requires:

- Expansion and modernization of the Nation's life sciences research facilities located at NASA's field centers, universities, and industrial centers
- Timely and sustained access to a range of space flight opportunities
- Recognition of the lengthy lead times required by these programs and of the funding requirements to accomplish the programs on time
- Development of a range of skilled program manpower.

The plan also highlights the advanced research and technology programs which are prerequisite items for human exploration missions, specifically in the areas of life support, suits, and better understanding of the biological effects of the radiation environment.

The President's FY 1991 budget request provides for the implementation of the programs and projects described in this plan. It fully supports the assembly of the life sciences knowledge base required for the EDO missions and the SSF program on a schedule compatible with the SSF Critical Design Review schedule. The budget request also supports science and technology requirements definition in the areas of radiation and life support technologies for future human missions.

APPENDIX

REFERENCE DOCUMENTS

1. 1979 - *Life Beyond the Earth's Environment: The Biology of Living Organisms in Space* (The Bricker Report), Space Science Board, National Research Council

2. 1985 - *Research Opportunities in Human Behavior and Performance*, EDS: J.M.Christensen and J.M.Talbot , Life Sciences Research Office, Federation of American Societies for Experimental Biology (NASA Contractor Report 3886)

3. 1987 - *Space Technology to Meet Future Needs* (The Shea Report), Committee on Advanced Space Technology, Aeronautics and Space Engineering Board, Commission on Engineering and Technical Systems, National Research Council

4. 1987 - *A Strategy for Space Biology and Medical Science for the 1980's and 1990's* (The Goldberg Report), Committee on Space Biology and Medicine, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council

5. 1988 - *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015, Life Sciences* (The Swisher/Usher Report), Task Group on Life Sciences, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council

6. 1988 - *Exploring the Living Universe: A Strategy for Space Life Sciences* (The Robbins Report), Life Sciences Strategic Planning Study Committee, NASA Advisory Council

United States General Accounting Office

GAO

Report to the Chairman, Committee on Science, Space, and Technology, House of Representatives

March 1990

SPACE OPERATIONS

NASA Is Not Properly Safeguarding Valuable Data From Past Missions

GAO
United States
General Accounting Office
Washington, D.C. 20548

Information Management and
Technology Division

B-237585

March 2, 1990

The Honorable Robert A. Roe
Chairman, Committee on Science, Space,
and Technology
House of Representatives

Dear Mr. Chairman:

This report assesses how well NASA is managing, storing, and archiving space science data acquired from its past missions and identifies a number of problems and challenges that NASA faces in ensuring the integrity and utility of massive volumes of valuable scientific data. As agreed with your office, we will issue another report at a later date on whether a mechanism exists for obtaining input from the scientific community on what types of space science data should be preserved and archived.

As arranged with your office, unless you publicly release the contents of this report earlier, we plan no further distribution until 30 days after the date of this letter. At that time, we will send copies to other appropriate congressional committees; the Administrator, NASA; the Administrator, General Services Administration; the Archivist of the United States; and make copies available to other interested parties upon request.

This work was performed under the direction of Samuel W. Bowlin, Director for Defense and Security Information Systems, who can be reached on (202) 275-4649. Other major contributors are listed in appendix VII.

Sincerely yours,

Ralph V. Carlone

Ralph V. Carlone
Assistant Comptroller General

Executive Summary

Purpose

The National Aeronautics and Space Administration (NASA) is responsible for space exploration and the management, archiving, and dissemination of space science data. Since 1958, the agency has spent about $24 billion on its space science program and successfully launched over 260 scientific missions. Data from these missions have expanded our understanding of the earth, its solar system, and the universe. Through these past missions NASA has acquired a massive volume of data stored on an estimated 1 million reels of magnetic tape for immediate and long-term scientific use. The nation's long-term ability to monitor changes in the earth's environment, such as the depletion of ozone and the destruction of tropical rain forests, may depend on data from early missions.

Future missions are expected to produce additional volumes of data unparalleled in NASA's history. Two missions—the Earth Observing System and the Hubble Space Telescope—are expected to generate more data than NASA collected during the past 30 years, and will likely require the use of advanced data storage technologies.

Given the nation's investment in space exploration, the data's long-term value, and the need to safeguard this irreplaceable information, the House Committee on Science, Space and Technology asked GAO to assess how well NASA is protecting the tapes containing this information from loss and deterioration.

Background

Because many of the data from past missions are irreplaceable, they should be managed as a valuable national resource. NASA stores most of these data on magnetic tapes. Federal regulations, established by the National Archives and Records Administration (NARA) and the General Services Administration (GSA), require government agencies to follow specific regulations in the management, maintenance, and storage of magnetic tapes. These regulations were adopted to ensure the long-term preservation of data stored on magnetic tapes, the prompt disposal of unneeded tapes, and the efficient management of storage resources. NARA and GSA are responsible for periodic reviews of NASA's and other federal agencies' data management and archival activities.

Results in Brief

Currently, hundreds of thousands of tapes containing space science data are stored under deplorable conditions. Furthermore, NASA needs to improve its management of tape archiving and storage activities. It has not performed an agencywide inventory of its magnetic tapes and, consequently, does not know what data are retained, or may have been lost, nor can it easily identify or retrieve tapes being stored in its centers or at universities. Further, NASA has not enforced federal regulations or developed its own standards for minimum acceptable storage, maintenance, security and quality control, and inventory practices.

NASA has several steps underway or planned to address certain aspects of the problems noted. However, without the allocation of adequate resources to improve the tape storage and archival facilities, the continuing deterioration of the magnetic tapes may result in the permanent loss of irreplaceable space science data. Moreover, unless it continues to improve its management of space science data, NASA will be hard-pressed to effectively and efficiently handle the massive volumes of data expected from its future missions.

Principal Findings

NASA Stores Many of Its Tapes Under Substandard Conditions

Eight of the 10 tape storage and processing facilities GAO visited did not comply with at least two of the applicable federal regulations established by NARA. Five of these facilities, which store almost 500,000 of the 1.2 million tapes identified by GAO, did not comply with more than half the combined federal regulations and industry tape management guidelines. These facilities did not have adequate temperature and humidity control, fire protection, water protection, or tape maintenance. In some instances, GAO found tapes stored in hallways, basements, and dusty warehouses not designed for tape storage. For example, in one major facility GAO found nearly 300,000 tapes packed in boxes covered by dust and stacked on shipping pallets.

A general lack of security also poses a serious threat to NASA's computer resources and space science data holdings. Some facilities GAO visited lacked even a rudimentary access control to guard against unauthorized entry into computer rooms and tape storage areas. Only one facility maintained backup tapes of original data so they could be restored if the originals were stolen or accidentally lost or destroyed. Consequently, without a secure environment, hundreds of thousands of magnetic tapes are susceptible to loss.

In contrast, a good storage environment is possible. Two facilities GAO visited complied with most of the applicable federal regulations and industry tape storage guidelines.

NASA Has Not Performed an Agencywide Inventory of Tape Holdings

NASA does not know how many space science data have been retained or archived on magnetic tapes since it began space exploration in 1958. At the facilities it visited, GAO identified almost 1.2 million NASA tapes, which were stored and managed by various NASA and contractor operated data processing or tape storage facilities, academic institutions, or other federal agencies. Although every facility GAO visited maintained an inventory of its tape holdings, these varied in completeness.

Data Archiving for Past Missions Was Treated as a Low Priority Activity

NASA has not provided adequate management leadership or funding for its past archival efforts. No one was assigned overall responsibility to ensure that these activities were effectively preserving space science data; instead, the data archiving responsibilities were diffused among NASA's headquarters, field centers, and space science mission officials.

NASA has not enforced federal tape management regulations, or developed or adopted agencywide standards for minimum acceptable tape storage conditions, routine tape cleaning and maintenance, security and quality control, and inventory practices. Furthermore, although NARA and GSA are responsible for conducting oversight reviews of NASA's tape management program to assess its effectiveness and identify areas needing improvements, neither of these agencies has done so. As reasons for not doing so, NARA cited a lack of resources, and GSA offered no explanation but said it plans to strengthen oversight activities.

According to NASA and Jet Propulsion Laboratory officials involved in archiving space science data, these activities were often underfunded. This assessment was echoed by the National Research Council's Committee for Data Management and Computation which recommended in 1986 that NASA establish a budget providing balanced support not only for spacecraft development and mission operations, but also to process, analyze, and archive the acquired space science data. The Committee also noted that the management and archiving of space science data are as important as mission operations, and recommended that NASA allocate additional resources to its long-term space science data handling and archiving activities.

NASA Has Several Improvement Efforts Underway

NASA recognizes that significant efforts will be required to correct the problems noted. Among the positive steps taken are limited tape restoration programs, establishment of a task force to reassess the management of data, and a census of data stored at several locations.

Recommendations

GAO is making a series of recommendations to the Administrator of NASA to help ensure that its valuable space science data from past missions are adequately stored, maintained, and preserved. These include recommendations that NASA (1) conduct a thorough inventory of data, (2) assess their scientific value, (3) copy valuable data and release unneeded tapes for reuse or disposal, and (4) archive the data in facilities that meet NARA regulations. Four additional recommendations focus on management improvements by (1) developing and implementing appropriate standards, (2) clearly defining management roles and responsibilities, (3) ensuring that periodic oversight is performed, and (4) allocating adequate resources to data management and archiving activities. Details on GAO's recommendations to NASA, as well as others made to GSA and NARA, are in chapter 4.

Agency Comments

In commenting on a draft of this report, NASA strongly believes it is safeguarding space science data as a national resource for future generations, but recognized there was room for improvement and said it was addressing GAO's recommendations in ongoing or planned programs. While NASA's limited inventory and tape restoration programs are discussed in the report, its plans for implementing GAO's other recommendations are still evolving, and as such, could not be evaluated.

NASA questioned the report's fairness, balance, and tone. GAO thinks the report fairly describes NASA's management of space science data holdings from past missions. Recognizing that NASA has several important improvement efforts underway, GAO nevertheless believes that the serious conditions under which hundreds of thousands of tapes from past missions are stored, combined with the low priority accorded this important activity, unquestionably substantiate the report's conclusions and recommendations. GAO believes that unless NASA addresses the serious tape management and storage problems noted, irreplaceable data will in fact be lost to future generations.

GSA said it had strengthened its management oversight function. NARA agreed that data management had a low priority in NASA and believed this was applicable to records management as well. An evaluation of the comments made by NASA, NARA, and GSA (see appendixes IV, V, and VI) is included in chapter 4.

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Abbreviations

CODMAC	Committee on Data Management and Computation
GAO	General Accounting Office
GSA	General Services Administration
IMTEC	Information Management and Technology Division
IRM	Information Resources Management
IRAS	Infrared Astronomical Satellite
JPL	Jet Propulsion Laboratory
NARA	National Archives and Records Administration
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NSSDC	National Space Science Data Center
TSSF	Tape Staging and Storage Facility

Chapter 1

Introduction

Since 1958, the National Aeronautics and Space Administration (NASA) has spent over $24 billion on space science. NASA has launched over 260 major space science missions and acquired, processed, and distributed massive volumes of data. It has helped to expand and deepen our understanding of our planet, solar system, and the universe. The data from these missions now includes well over a million reels of magnetic computer tape representing a significant national resource needed for future research.

Under the National Aeronautics and Space Act of 1958, Congress made NASA responsible for space exploration research and directed it to provide for the widest practicable and appropriate dissemination of space exploration information. The Office of Space Science and Applications is assigned overall management responsibility for NASA's data, while the Office of Management provides agencywide oversight of information resources management activities. The National Archives and Records Administration (NARA) and the General Services Administration (GSA) are responsible for periodic reviews of NASA's and other federal agencies' activities in managing and archiving their data.

NASA's Space Science Data Are Stored on Magnetic Tapes

The majority of data from past NASA missions is stored on at least 1.2 million magnetic tapes which have the capacity to store over 90 billion pages of text.[1] Although the agency is already storing massive amounts of data, these amounts will be dwarfed by the expected stream of data from its future missions. For example, the chief scientist for the Earth Observing System estimates that the system, scheduled for launch in 1998, is expected to generate one terabit[2] of data each day for at least five years. According to the Library of Congress' Assistant Director for Research, given this volume of data, every 12 weeks the Earth Observing System spacecraft will generate a volume of data[3] equivalent to the text contained in all 15 million books held by the Library of Congress. NASA has made the National Space Science Data Center (NSSDC) its principal archival and data dissemination facility. NSSDC, located at the Goddard Space Flight Center (Goddard) in Greenbelt, Maryland, manages over 113,000 magnetic tapes. NASA also stores over a million tapes in a variety of NASA or contractor-operated storage facilities. The Tape Staging and Storage Facility (TSSF), in Landover, Maryland, is the largest, with responsibility for storing and tracking over 860,000 tapes from missions managed by Goddard. An unknown volume of NASA tapes is also stored by individual scientists and research teams at major universities. NASA's tapes are aging, with a growing number at least 15 to 20 years old.

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[1] This estimate is based on the storage capacity of a standard 2,400 foot long tape, with data stored at 6,250 bits per inch.

[2] One terabit of data equals to 10^{12} bits (1,000,000,000,000 or 1 trillion bits). About 700 high density (6,250 bits per inch) tapes would be required to store 1 terabit of data.

[3] This estimate is based on assumption that an average book contains 300 pages of text, with 400 words per page and 6 characters per word.

Magnetic Tapes Require Maintenance

In the last two decades, computer magnetic tape emerged as the prevalent mass storage medium used by industry and government for both intermediate and archival data storage. Magnetic tape is durable, portable, and relatively cheap but must be properly managed, maintained, and stored to prevent data losses. Federal regulations and guidelines require government agencies to follow specific standards in the management, maintenance, and storage of magnetic tapes. These standards were adopted to ensure the long-term preservation of valuable data stored on magnetic tapes and the efficient management of storage resources.

According to NARA, the International Council on Archives, and industry, a magnetic tape that has been properly stored and maintained may last about 10 years. General industry practices and proposed NARA regulations require that all tapes 10 years old be copied. Data deterioration or losses are mainly due to physical damage to tape caused by mishandling, contamination, and poor storage environment.

NASA's Space Science Data Are a Valuable National Resource

Because many of the data retain their scientific value indefinitely and are difficult and costly to acquire, the scientific community sees them as a significant national resource that must be safeguarded and preserved. Although there are numerous characteristics determining the long-term value of scientific data, scientists agree that in general these include data that:

- are unique and may not be replicated by future missions;
- may be related to or enhanced by data acquired by other past and future missions;
- may be needed to plan future missions;
- entail continuous, multiyear, global coverage and may be needed for studies of long-term environmental changes;
- were not fully analyzed;

- were processed using old computer technology and analytical techniques and should be reprocessed and reanalyzed; and
- are of significant historical interest.

An argument for the preservation of data was also made by the National Research Council's Committee on Data Management and Computation (CODMAC) which noted that:

> "Many of the uses of the [space science] data cannot be foreseen in advance. Frequently, new ideas for uses of the data emerge long after the data are acquired, as a result of the continuously evolving understanding of the physical processes under study... Even though some of the acquired data may never be fully utilized, it is often not possible to decide in advance which data will be of critical value in gaining future new scientific understanding."[4]

The long-term value of data and the need to preserve selected data from earlier missions are underscored by the need to develop multiyear data bases which would allow scientists to measure and track global changes in earth's environment. For example, the recent effort to evaluate the extent and impact of the global depletion of atmospheric ozone, the destruction of the tropical rain forests, and the changes in global drought patterns may require developing and using data bases that include data from earlier earth observation missions.

Future Data Pose Significant Challenges

During the next two decades, NASA will face significant challenges managing and archiving its data. Between 1980 and 2000, NASA has or plans to support 84 missions in four scientific disciplines, including planetary and lunar, earth sciences, space physics, and astrophysics. These missions will produce a volume of data unparalleled in NASA's history. For example, two of the planned missions, the Earth Observing System and the Hubble Space Telescope are expected to generate amounts of data many times greater than NASA has collected over the past 30 years. NASA scientists who develop advanced science data management systems recently noted that:

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[4] *Issues and Recommendations Associated With Distributed Computation and Data Management Systems for the Space Sciences*, Committee on Data Management and Computation, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council, National Academy Press, Washington, D.C., 1986, p. 104.

"…. it is anticipated that the future ability of NASA to function and perform meaningful space and earth related research will be significantly affected by its inability to manage and use its collected information to derive knowledge."[5]

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[5] The Development of a Prototype Intelligent User Interface Subsystem for NASA's Scientific Database Systems, NASA Technical Memorandum 87821, June 1987, p. 1.

NASA's Tape Management Practices Place Space Science Data at Risk

NASA has failed to properly store, maintain, and manage its magnetic tapes containing valuable and irreplaceable data. It has not performed an agencywide inventory of its magnetic tapes and does not maintain a central listing of its data holdings. Therefore, NASA neither knows how many data were retained or lost on magnetic tapes since 1958, nor can it easily identify or retrieve data being stored. Problems with NASA's data archiving activities are not new. Several problem areas needing attention were identified by us and others in 1977, 1982, and 1988. Although there could be more, our review identified about 1.2 million tapes stored at various NASA and contract data processing or storage facilities, academic institutions, and other federal agencies.

NASA has no tape management standards of its own, and has failed to properly store or manage its magnetic tapes in accordance with standards established by NARA, GSA, National Institute of Standards and Technology (NIST), and tape manufacturers' instructions. As a result, the valuable and often irreplaceable data acquired by NASA at a cost of billions of dollars, are being managed and stored under deplorable conditions. According to JPL officials, many of its older data stored on magnetic tapes are deteriorating because of aging, lack of maintenance, and poor storage conditions. They noted that almost all of NASA's data are at risk, including holdings at universities and NASA centers. Moreover, some important data may have been irretrievably lost. For example, we found several hundred thousand magnetic tapes packed in boxes stored on loading pallets, strapped with steel bands under substandard conditions, and without adequate environmental control or maintenance. Accordingly, much of the data may be deteriorating and at risk of being permanently damaged or lost.

NASA has taken several steps to address the deterioration of its magnetic tapes, including limited and costly restoration of older tapes and transfer of selected data from older tapes to optical disks. However, we believe that NASA could have avoided the relatively high restoration costs[1] through proper storage and maintenance.

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[1] NSSDC officials estimated that the center has spent about $250,000 to restore 8,760 tapes, at an average cost of $28 per tape. Similarly, JPL restored 12,500 tapes at a cost of $466,000, or about $37 per tape.

NASA Has Not Performed an Agencywide Inventory of Its Space Science Data Holdings

NASA's tapes containing space science data are stored in various NASA and contractor facilities located at or near NASA field centers, as well as at numerous other locations. In general, these data fall into two categories: (1) raw and intermediate data,[2] and (2) data designated by scientists and by NASA as a formal archival product.[3] Raw and intermediate data are stored in many places, including NASA, contract tape storage facilities, federal records centers, other federal agencies, universities, and research institutions. NSSDC is NASA's principal facility responsible for archiving and distributing archival data.

NASA has not performed an agencywide inventory to determine the amount, type, and location of data collected and retained on magnetic tapes since it began space exploration in 1958. Moreover, because it does not maintain a central listing of its tapes, many of the stored data cannot be easily identified or retrieved. However, every facility we visited maintained inventories and data directories of their own tape holdings which varied in quality and completeness. For example, NSSDC maintains an automated inventory and catalog of all its tapes, while TSSF maintains only a partial inventory, and JPL's inventory of 130,000 tapes stored at the Federal Records Center in Laguna Niguel consisted of a listing of stored boxes, without details of the contents. During the course of our review, NASA advised us that it recognized the need for a comprehensive, agencywide inventory of these data and is planning to conduct a census of its space science tapes. NASA is also developing a master directory designed to provide electronic access to data catalogs. These and other initiatives are discussed in more detail in chapter 3.

In the absence of an agencywide inventory or central listing of magnetic tapes containing space science data, we relied on other sources of information, including NASA documents and interviews with NASA and JPL[4] officials, to identify facilities managing and storing NASA's tapes. Based on this information, we identified the NASA facilities we believe to be managing the bulk of NASA's data. Specifically, over 1.2 million magnetic tapes are managed or stored at NSSDC, Goddard's TSSF, JPL, and at the federal records centers in Washington, D.C., and Laguna Niguel, California. Nearly 50,000 tapes were also stored by three university-based institutions and one federal data center. Although there could be more, these facilities collectively store or manage about 1.2 million NASA tapes. We visited every facility listed below:

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[2] The intermediate data include the original data transmittedby the spacecraft, and certain processed data, including ancillary information such as instrument calibration and spacecraft position. NASA provides these data to the scientists for their analysis.

[3] NASA identifies two types of archival data — the analyzed data records and the reduced data records. The analyzed data records are ones which the scientist designates as the best to display the scientific results of an experiment. The data are usually calibrated and may include only selected observations. The reduced data records include data modified by the scientists to include corrections for temperature, voltage, spacecraft drift, and other factors. Both types of data are produced by scientists under contract to NASA to analyze data acquired by specific missions or instruments. After completion of data analysis, the scientists create data sets for NASA archives.

[4] The Jet Propulsion Laboratory is managing magnetic tapes containing space science data from planetary missions. Until late May 1989, the Laboratory was storing approximately 130,000 tapes at the Federal Records Center in Laguna Niguel, California. These tapes are now stored at JPL.

Table 2.1: Selected Tape Processing and Storage Facilities Managing NASA Space Science Data

Facility	Location
National Space Science Data Center	Goddard, Greenbelt, Maryland
Tape Staging and Storage Facility	Landover, Maryland
Los Angeles Federal Records Center	Laguna Niguel, California
Washington National Records Center	Washington, D.C.
Smithsonian Astrophysical Observatory	Cambridge, Massachusetts
Multi-mission Image Processing	JPL, Pasadena, California
Data Protection Services	Dominguez Hills, California
Infrared Processing and Analysis Center	California Institute of Technology, Pasadena, California
Center for Astrophysics and Space Sciences	University of California, San Diego, La Jolla, California
EPOS Data Center	Sioux Falls, South Dakota

The Federal Government and Industry Prescribe Tape Management Standards

Poor management of magnetic tapes may cause partial or total loss of recorded data. Although a modern magnetic tape is sturdy and may last for up to 10 years, and research and empirical evidence have shown that the magnetic signal may remain strong indefinitely, the tape itself will deteriorate unless properly maintained. (Appendix II discusses the characteristics of magnetic tapes.) Concerns in government and industry about the preservation of magnetic tapes led NARA, NIST,[5] the International Council on Archives, and the industry to develop comprehensive tape management standards. These standards fall into two groups: federal regulations established by NARA;[6] and NIST[7] and industry[8] guidelines.

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[5] NIST conducts research and provides technical services designed to help federal agencies run their programs more cost effectively.

[6] Code of Federal Regulations, Title 36, Part 1234.

[7] Care and Handling of Computer Magnetic Media, NBS Special Publication 500-101, National Bureau of Standards, June 1983. (NBS is now called NIST.)

[8] We contacted eight manufacturers of magnetic tapes or peripherals, one tape management consulting firm, and the International Council on Archives, and obtained their tape management guidelines.

Together, they constitute a set of safeguards and practices that are designed to reduce the potential loss of valuable data stored on magnetic ta s.

According to NIST, losses of data stored on magnetic tapes stem from contamination and physical or chemical deterioration of tapes due to inadequate housekeeping techniques such as lack of cleanliness, inadequate temperature and humidity control, the absence of tape maintenance, and improper tape handling. Data stored on damaged, contaminated, or deteriorated tapes can sometimes be partially or fully recovered through costly restoration and recovery procedures. Some data are completely lost.

Because NASA had not adopted the federal regulations as agency policy or developed its own tape management guidelines, we developed a tape management checklist, based on federal regulations, and NIST and industry guidelines, to assess each facility's practice. (Appendix I has more information on how we performed this assessment.) Although these regulations and guidelines cover many aspects of tape management, they focus on crucial factors in preserving magnetic tapes:

Covered by Federal Regulations

- temperature and humidity control;
- proper preparation of archival tapes designed for long-term storage;
- backup and storage of tapes containing valuable data at another location;
- adequate security and internal controls to safeguard equipment, software, and tapes from theft, tampering, or destruction; and
- quality control to detect deterioration of stored tapes.

Covered by Federal and Industry Guidelines

- clean environment and handling to prevent tape contamination and damage;
- fire protection;
- water protection;
- tape drive maintenance to eliminate hardware-related tape damage;
- routine, scheduled tape maintenance program; and
- tape transportation safeguards.

Lack of Compliance With Federal and Industry Standards

Eight of the 10 tape storage and processing facilities we visited did not comply with at least 2 of the federal regulations established by NARA. Further, 5 of these facilities, which store almost 500,000 of the 1.2 million tapes identified, did not comply with more than half the combined federal regulations and industry tape management guidelines. These facilities failed to meet such criteria as adequate temperature and humidity control, fire protection, water protection, or tape maintenance. In some instances, we found tapes stored in hallways, basements, and dusty warehouses not designed for tape storage. More important, we found some of the most significant tape management deficiencies in the two largest facilities responsible for managing irreplaceable data — NSSDC and TSSF. A good storage environment is possible. Two facilities we visited—the U.S Geological Survey's EROS Data Center and the Digital Equipment Corporation's Data Protection Services—were in full or partial compliance with most applicable federal regulations and industry guidelines.

The following table lists individual regulations and guidelines and the level of compliance we found during our review.[a] In noting the compliance level, we assigned

- a full compliance rating where total compliance with all regulations or guidelines was observed or documented;
- a partial compliance rating where the facility did not comply with one or more regulations or guidelines;
- a non-compliance rating where compliance with none of the regulations or guidelines was observed or documented; and
- a non-applicable rating where the facility was not responsible for certain aspects of tape management such as quality control.

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[a] Subsequent to our visits, several facilities implemented or plan to implement various corrective actions. These actions are discussed in appendix 3.

Figure 2.1: Compliance With NARA's and Industry Tape Management Standards

NARA Regulations	National Space Science Data Center	Smithsonian Astrophysical Observatory	Multi-mission Image Processing Laboratory	Infrared Processing and Analysis Center	Center for Astrophysics and Space Sciences	EROS Data Center	Data Protection Services	Tape Staging and Storage Facility	Federal Records Center, Laguna Niguel	Washington National Records Center
Temperature control	○	○	△	△	○	●	●	○	○	△
Humidity control	○	○	○	△	○	●	●	○	○	△
Test/certify media	○	○	○	○	○	○	NA	NA	NA	NA
Off-site backup	△	△	△	●	△	○	NA	NA	NA	NA
Security										
Computer room	○	○	△	○	○	●	NA	NA	NA	NA
Tape library	○	○	△	○	○	●	●	△	△	△
Sample 3% of tapes	○	○	○	○	○	△	NA	NA	NA	NA
NIST and Industry Guidelines										
Tape handling	△	○	△	○	△	●	●	○	NA	NA
Fire protection	△	○	△	△	△	●	●	△	△	△
Water protection	○	○	△	○	○	○	●	○	△	△
Hardware maintenance	●	△	●	●	△	●	NA	NA	NA	NA
Tape maintenance	○	△	○	○	△	△	NA	NA	NA	NA
Tape transportation	○	○	○	○	○	NA	△	○	○	○

● Full compliance
△ Partial compliance
○ Noncompliance
NA Not applicable

Most facility managers generally agreed with our findings, and in many instances are planning to correct the deficiencies. Asked to name what, in their opinion, caused these deficiencies, the managers listed: (1) lack of knowledge about NARA tape management regulations, (2) budgetary constraints and the high cost of complying with every regulation,

(3) storage space limitations, (4) desire to maintain easy access to data unhampered by stringent security and access control, and (5) a belief that the various deficiencies had not caused an actual loss of stored data. Appendix III presents their detailed responses to our findings.

The following section contains our summary assessment of how well the 10 facilities implemented procedures and safeguards related to the critical factors.

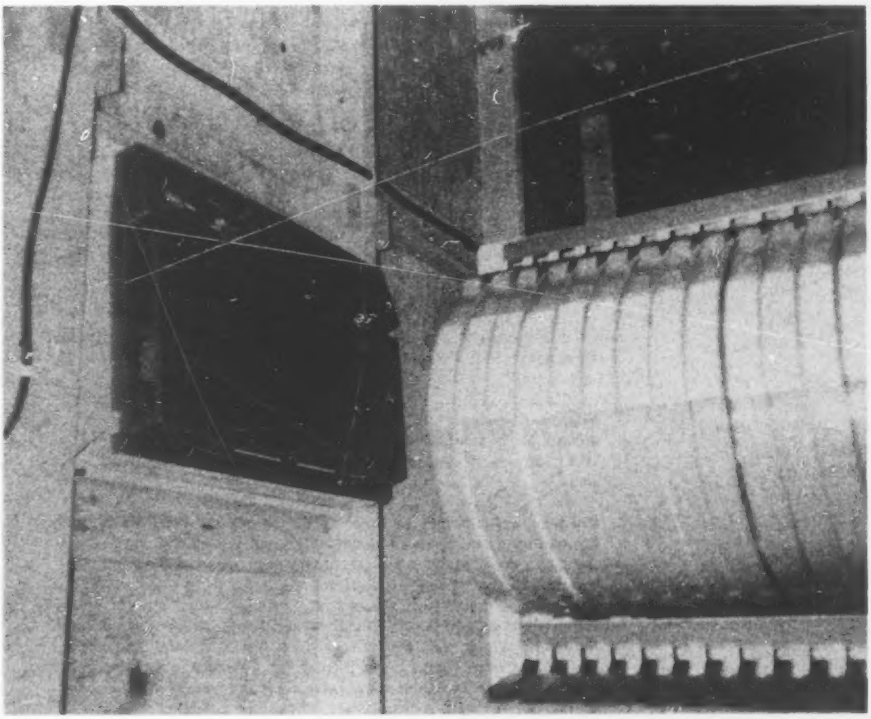
Temperature and Humidity Control

Only two facilities implemented adequate environmental controls. Eight facilities, including NSSDC, TSSF, and two federal records centers, either lacked temperature and humidity recorders, or stored tapes in areas where recorders were not calibrated.

To avoid environmental damage, NARA requires that the operating, storage, and test area in tape processing and storage facilities be kept at 60 to 72 degrees Fahrenheit and between 40 to 50 percent humidity. Extreme temperature and humidity levels or repeated temperature and humidity changes cause permanent tape damage and loss of data.

Figure 2.2 shows a wall-mounted air conditioning unit discharging refrigerated air directly on NASA tapes at one of the tape storage facilities we visited.

Figure 2.2: Tapes Stored Next to an Air Conditioning Unit



Preparation of Archival Tapes

None of the facilities we reviewed tested and certified all new tapes. NARA requires that all tapes designated for permanent retention should be tested and certified no more than 6 months before they are used for long-term storage. This regulation is designed to assure the long-term preservation of the recorded data by removing contaminants and ensuring that the tape is free of manufacturing defects. Although most manufacturers test tapes before shipment, that does not guarantee a defect-free tape. According to the NIST, new tapes are sometimes contaminated with debris, and so, unless tested and certified, they will eventually become the source of errors when the data is written to or read from the tape.

Off-Site Backup of Original Tapes

Only one facility, the Infrared Processing and Analysis Center, which is responsible for managing data acquired by the Infrared Astronomical Satellite, provided for full backup of their original tapes.[10] NARA requires that a duplicate of tapes containing valuable data be stored at an off-site location. This regulation guarantees that a full set of tapes is available should the originals be destroyed through vandalism, earthquake, flood, or fire.

Other facilities provided on-site backup for some but not all their tapes. Managers said full backup was too expensive.

Security and Internal Controls

Four of the facilities did not control access to computer rooms and tape storage areas. Inadequate security and access control may result in theft, tampering, or destruction of computer equipment, software, and data.

The lack of security at NSSDC illustrates the need to secure valuable data. For example, during an unannounced computer security check, Goddard's security report noted "the doors wide open... picked up tapes, browsed through facility for several minutes.... no challenge ... wandered around freely."[11] The security officer noted that this was a follow-up visit, and that the facility "may never start to correct" the deficiency. Figure 2.3 illustrates the lack of security and tape management controls we found at one facility, where a posted sign requests that users "sign out" for all archival tapes removed from the often unattended and unsecured tape library.

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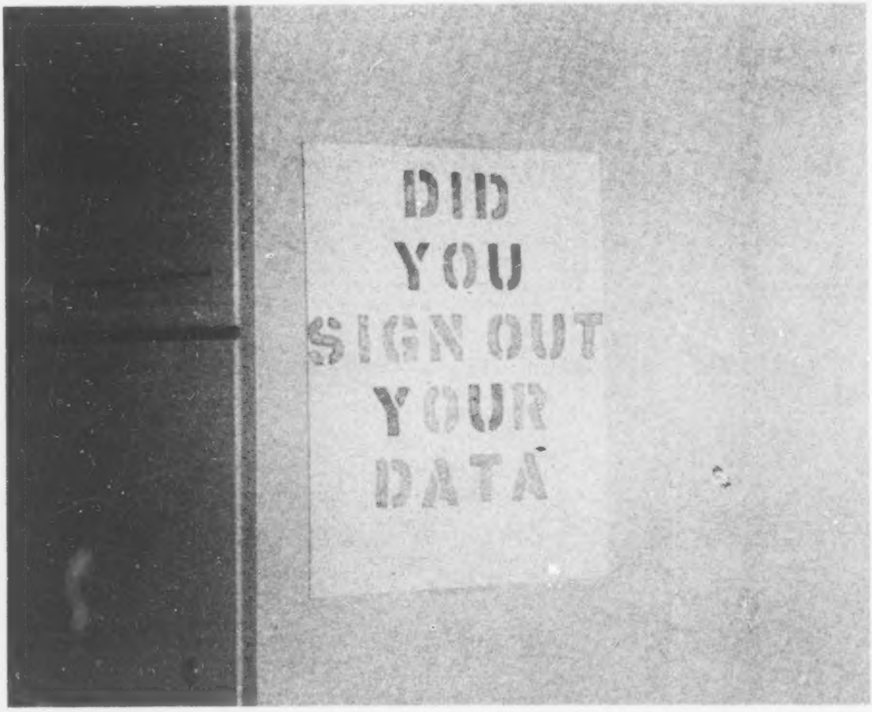
[10] According to Center officials, the full set of Infrared Astronomical Satellite (IRAS) data—including raw data from the mission, intermediate data, and all archival data—is also stored overseas. In the Netherlands, the data are archived at the University of Groningen and Sterrewach Huygens Laboratorium at the University of Leiden. In the United Kingdom, the archive facility is the IRAS Post Mission Analysis Facility at Rutherford Appleton Laboratory. A full set of archival data is also stored by NSSDC.

[11] "Unannounced Computer Security Check", Goddard Space Flight Center, October 20, 1987.

Figure 2.3: Sign Reminding Staff to Sign-Out for Archival Tapes When the Tape Library Is Unattended



The lack of security endangers valuable data, computer equipment, and software. In most instances, the effort and cost to correct the most significant deficiencies are minimal, and may require only a modest expenditure for a card access lock for the computer room, or changes in facility operating procedures.

Quality Control

Only one of six facilities responsible for the monitoring of their tapes performed any quality control of stored tapes. NARA requires that each federal facility storing magnetic tapes annually sample 3 percent of all holdings to detect deterioration.

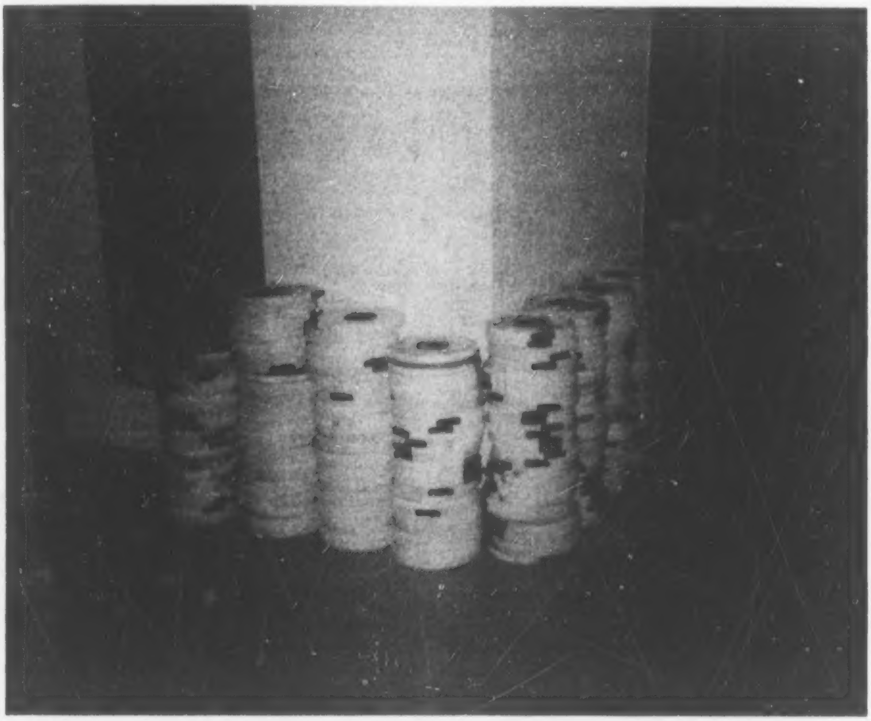
We agree that routine sampling and testing of stored tapes aids quality control. However, on July 11, 1989, we asked NARA to reevaluate its across-the-board 3 percent sampling regulation. Depending on the number of tapes stored, we were concerned that a fixed 3 percent sample without regard to statistical considerations, such as the size of the universe, could result in over or under-sampling, a potentially costly or risky practice. In September 1989, NARA officials informed us they were revising their regulations to require an annual sample size that would provide accurate results to within 5 percent at the 95 percent confidence level. Statistics aside, five facilities were not performing this valuable practice at all.

Clean Environment and Tape Handling

Three facilities either did not provide a clean environment for processing and storing magnetic tapes, or did not handle them in a manner designed to reduce tape contamination. Clean environment and tape handling standards cover a broad range of recommendations ranging from clean processing and tape storage areas to guidelines on the physical handling of tapes. Poor tape handling may cause tape contamination or physical damage and the loss of recorded data. For example, tapes may be contaminated through proximity to smoking, eating, and drinking. Other sources of contamination are stored paper products, inappropriate janitorial techniques, or dust-producing equipment such as high speed printers. Tapes may also be physically damaged by horizontal stacking, rough handling, or heat produced by computers and other equipment.

As shown in the following three figures, we found that several facilities were storing NASA tapes in a manner and in an environment conducive to damage. For example, Figure 2.4 shows one facility where we found hundreds of tapes stacked in a dusty hallway, while Figure 2.5 notes where we found over 4,000 tapes stored in a dirty basement subject to flooding. Finally, Figure 2.6 shows one facility where we found nearly 300,000 boxed tapes, stored on pallets, and strapped by steel bands. At this location, we observed instances where the downward weight of the tapes had warped the wooden pallets and the steel bands appeared to be crushing the contents of the tape storage boxes.

Figure 2.4: Tapes Temporarily Stored in a Hallway



Fire Protection

Eight facilities lacked adequate fire protection in their tape storage areas or were keeping combustible materials nearby. Two facilities had no smoke or heat detectors or automatic fire suppression systems. Eight had combustible materials stored in tape vaults and computer rooms.

Under NIST guidelines, tape storage vaults should: (1) have fire and smoke detectors, (2) have a fire suppression system, (3) be designed with fire protection as a major consideration, and (4) be free of combustible materials.

Figure 2.5: Tapes Stored in a Basement

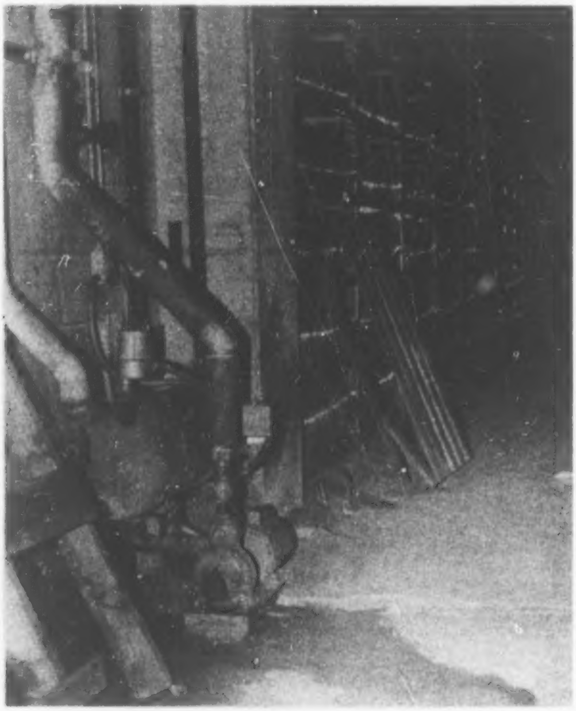


Figure 2.6: Tapes Stored on Pallets Strapped With Steel Bands

Figure 2.7 shows a ceiling-mounted electric heater installed next to a plywood wall discharging hot air directly on NASA tapes at one of the tape storage facilities we visited.

Water Protection

NIST and industry guidelines recommend (1) the installation of floor-based water detectors, and (2) the availability of plastic sheets to protect stored tapes from overhead leaks. Only one facility installed water detection devices in its tape storage area, and only three facilities had plastic sheets on hand to cover tape racks in case of a leak. Undetected water leaks or flooding significantly damage magnetic tapes unless they are promptly treated. For example, because of lack of funding and a shortage of tape storage space, one facility is storing 4,000 tapes in a sub-basement which was flooded in 1985. Figure 2.8 shows a portion of these tapes that were about half submerged during the flooding. Contaminants and debris left a clearly visible water line on the tapes. In another instance, a roof-based air conditioning unit leaked on boxes stored near NASA tapes, as shown in figure 2.9.

Figure 2.7: Electric Heater in Close Proximity to Stored Tapes

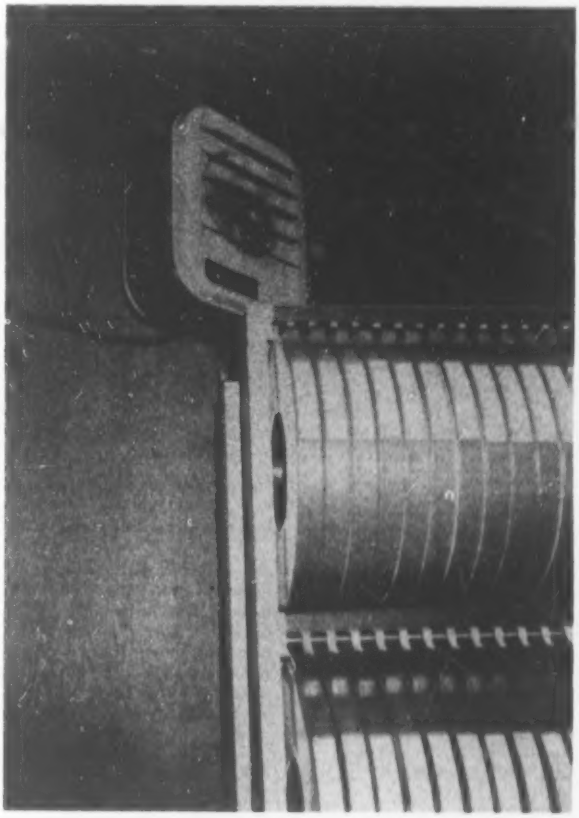


Figure 2.8: Tapes Likely Damaged by Flooding

Figure 2.9: Water Leak Near NASA Tapes

Tape Drive Maintenance

Two facilities did not adequately maintain their tape drives. Poorly maintained drives may cause immediate or delayed tape and data damage. NIST and industry guidelines recommend a scheduled hardware maintenance program that includes the frequent cleaning of tape write/read heads and the removal of accumulated debris in the tape transport components. Other maintenance care should be focused on the periodic demagnetization of these heads, and the alignment and lubrication of tape drive components.

Routine Tape Maintenance

None of the facilities adequately maintained their tapes. Scheduled maintenance of tapes is critical, especially for tapes stored in vaults with poor environmental controls. In general, NIST suggests that tapes be periodically cleaned, rewound, and, if required, copied.

Tape Transportation Safeguards

Only one facility protected its tapes in transit. According to NIST, such tapes should receive special care, including packing and transportation in climate-controlled vehicles. Transportation hazards include excessive vibration, exposure to contaminants and stray magnetic fields, and extreme and uncontrolled temperature and humidity changes.

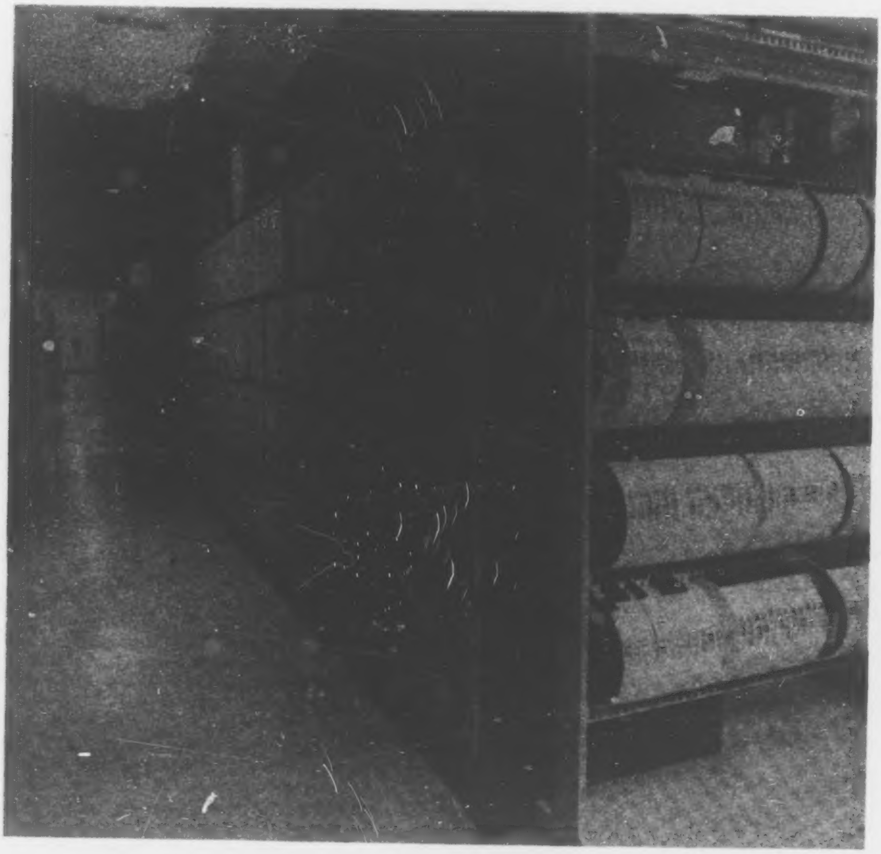
A Good Storage Environment Is Achievable

We visited two tape storage facilities with reputations for excellence in tape storage practices—the Digital Equipment Corporation's Data Protection Services, a commercial tape storage facility in Dominguez Hills, California, and the EROS Data Center, a federal facility in Sioux Falls, South Dakota.

The Dominguez Hills Data Protection Services provided tape archival and storage services to government agencies and to the private sector. The facility was under contract to JPL to store over 15,000 tapes. We found that its tape library fully met federal regulations and industry storage environment guidelines. Since our visit, the Dominguez Hills facility closed, and the laboratory transferred its tapes to another commercial facility in February 1989.

The U.S Geological Survey's EROS Data Center is responsible for processing, analyzing, archiving, and distributing remote land-sensing images acquired by the Landsat satellites and other remote land-sensing instruments flown on NASA and the National Oceanic and Atmospheric Administration's missions. The center manages over 117,000 tapes. We found the center's tape library, as shown in figure 2.10, to be in full or

Figure 2.10: EROS Data Center Tape Storage Vault



partial compliance with most of the applicable federal regulations and industry guidelines. It clearly demonstrates that a good tape storage environment is achievable.

NASA's Data Restoration Efforts

Recognizing that many of its tapes are deteriorating, NASA has taken steps to restore or preserve selected tapes held at NSSDC and JPL. Given limited resources, NASA does not plan to restore the hundreds of thousands of un-inventoried aging tapes stored in other NASA facilities, universities, and research institutions.

JPL's Restoration Programs

Concerned about the potential deterioration of its magnetic tapes, JPL restored approximately 12,500 tapes containing over 130,000 digital images from the Voyager, Viking, and Mariner 9 and 10 missions. These tapes had been stored at the Federal Records Center at Laguna Niguel and elsewhere.

According to the manager, this generally successful restoration, which cost $495,000 and took from 1983 to 1984, revealed that the attempt to restore tapes over 10 years old can often destroy them. Once the magnetic oxide coating has deteriorated, the tapes can be read only once, because reading recorded data strips their magnetic oxide layer. Thus, if the first reading was unsuccessful, the project could not recover the stored data on subsequent readings.

In July 1986, the laboratory sent a team to inspect its 130,000 remaining tapes stored at the Federal Record Center in Laguna Niguel and to assess possible damage caused by an earthquake. The team found that several shelves holding the laboratory's tapes received severe shaking and that several boxes containing tapes had fallen from the top shelves. Many sections of the acoustic ceiling had also been shaken loose. The team noted that "... the dust created by the falling sections into the boxes has surely contaminated the tapes at this point."[12] This contamination could have been significantly reduced if JPL had shipped its tapes in sealed boxes. We observed a high proportion of the laboratory's tapes stored in unsealed or partially open boxes.

In briefing JPL's Associate Directors, the staff noted that the laboratory's tapes were stored in substandard facilities and without disaster recovery backup or procedures to assure proper management of its tapes. The staff recommended that the laboratory develop a policy for protecting, handling, and storing magnetic tapes and suggested that a new facility be found to store the more than 130,000 tapes being stored at the center. In a letter dated December 4, 1986, the center's director underscored the need for prompt action:

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[12] JPL Interoffice Memorandum - Federal Archives Earthquake Damage, July 14, 1986.

> "Our record center does not have an environmentally controlled storage conducive to the safe maintenance of computer magnetic tapes... You may store your magnetic tapes at this facility but we cannot guarantee the safe maintenance of your records."[13]

In December 1986, the laboratory began planning how to deal with these tapes. In discussing the potential preservation tasks, the staff noted:

> "JPL ALDs (Associate Laboratory Directors) have recently been made aware of the *deplorable conditions* under which JPL data and data tapes are maintained in the Federal Records Center in Laguna Niguel. Their concern has prompted JPL to seek storage for data tapes under better conditions, but the costs are prohibitive, like a dollar a tape a month, for the large number of data tapes currently being 'archived'."[14]

According to the project manager's estimate, probably half the 130,000 tapes stored at the center were either damaged or degraded beyond restoration or contain data no longer worth keeping. Tapes more than 10 years old were at risk, and the project would not be able to recover between 20-25 percent of them.

In April 1989, the laboratory initiated a project designed to remove and restore all tapes containing valuable data stored at the Federal Records Center in Laguna Niguel. The 5-year, $1.8 millon project is to be implemented in two phases. During the first phase, the laboratory was to remove, in stages, the 130,000 tapes stored at the center. These tapes are to be evaluated for data identification, tape and data condition, and the value of data. According to the project staff, this phase will take about 2 years to complete. During the second phase, tapes containing data identified as valuable are to be copied to new tapes. This phase is planned to be completed in 1994.

However, in its May 1989 letter to JPL, the Federal Records Center in Laguna Niguel noted that it cannot adequately store magnetic tapes, and that it would ship them to another federal record center better equipped to store them. In late May 1989, JPL moved all its tapes from Laguna Niguel to its facilities and started implementing the project's first phase.

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[13] Letter from the Federal Records Center in Laguna Niguel to JPL, December 4, 1986.

[14] "JPL Planetary Data Restoration Task Planning Meeting," JPL memorandum, December 8, 1986 (emphasis added).

NSSDC Data Restoration Project

In June 1988, NSSDC began a program designed to restore about 30,000 tapes, many which are over 10 years old and deteriorating. The NSSDC restoration project is restoring about 10,000 tapes annually. According to NSSDC officials, as of September 1989, the Center successfully restored over 8,700 tapes at a cost of about $250,000. This cost includes labor, new tapes, a new tape drive, and software. According to NSSDC officials, this restoration succeeded because most of the restored tapes were the relatively newer, high-density kind produced in the 1970s. But project staff noted that, although all data were restored, some tapes had so deteriorated that data extraction required several attempts, and the staff often had to recover lost data segments from backup tapes. For example, to restore data from an early mission, the restoration project staff had to hand clean over 200 degraded tapes. As the NSSDC begins to restore the older, low-density tapes, more problems will be encountered.

Some Stored Tapes May Contain Data of Marginal Value

NASA and some scientific institutions may be spending limited resources to store thousands of tapes containing data without appreciable scientific value. These tapes may contain data that (1) were superseded by similar data with higher precision or resolution, (2) are poorly documented and cannot be interpreted, (3) are of questionable quality and completeness, and (4) are stored on deteriorated tapes and cannot be fully recovered. For example, JPL officials estimated that about half their 130,000 tapes formerly stored at the Federal Records Center in Laguna Niguel are damaged beyond recovery or contain data of little scientific value. The question of data value also applies to NASA's formal archival data sets maintained by NSSDC on over 113,000 tapes. In 1983, a group of scientists participating in a planetary data workshop noted that:

> "The opinion that the current NSSDC is inadequate for curation, access, and distribution of planetary data is prevalent among users and data providers. Data archived there are of variable quality, some data sets have questionable accuracy, others are incomplete or have much lower temporal and spatial resolution than the original instrument data. Little processing history is provided with the data, and engineering information (when available) is supplied in hardcopy."[15]

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[15] Trends in Planetary Data Analysis, Executive Summary of the Planetary Data Workshop, NASA Conference Publication 2333, 1984,p. 6.

NASA has taken steps to strengthen its archiving of planetary data through its Planetary Data System.[16] However, according to its manager, the system currently incorporates only a fraction of these data. The system is currently restoring data from past planetary missions, and eventually plans to incorporate most of these data in its data base. However, the system manager noted that there is no schedule for the completion of this effort, and that its completion is dependent on the resources NASA allocates to this task. If the conditions noted above also apply to data from other scientific disciplines, their value may also be questioned.

Chronic Problems in NASA's Archiving of Space Science Data Have Been Noted Before

An earlier GAO review and scientific advisory group reports noted chronic problems in NASA's data archiving practices and expressed concerns regarding the long-term preservation of data. In our 1977 report, we found that the acquired data was not archived in a timely manner, and that NASA was not enforcing its regulations concerning the archiving of data prepared by Principal Investigators.[17] In a 1982 report,[18] CODMAC noted that:

- data system and data analysis, including data archiving, were not adequately funded;
- data archives generally contained insufficient or inaccurate information about the archived data;
- data management responsibilities for both during and/or post mission phases were not clearly identified;
- archived data were often destroyed without consultation with the scientific community; and
- in some cases data acquired from past missions have not been properly archived.

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[16] This JPL-based advanced data management and archiving system will consist of five or more electronically connected nodes responsible for processing, archiving, and disseminating data from past and future planetary missions. Using optical data storage technology, it is producing two Compact Disk Read Only Memory (CDROM) disks containing 4,000 Voyager images of Saturn and three disks containing 6,000 Jupiter images. NASA established the system in response to scientists' call for the development of a distributed data management and archival system operated and maintained by scientists.

[17] More Emphasis Needed On Data Analysis Phase of Space Science Programs (PSAD-77-114, June 27, 1977).

[18] Data Management and Computation, Volume 1: Issues and Recommendations, Committee on Data Management and Computation, Space Science Board, Assembly of Mathematical and Physical Sciences, National Research Council, National Academy Press, Washington, D.C., 1982, pp. 2-4.

Similarly, in its most recent report, CODMAC recommended that NASA should develop procedures to protect its data archives from deterioration of media, hardware failures, and tampering by individuals.[11]

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[11] Selected Issues in Space Science Data Management and Computation, Committee on Data Management and Computation, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council, National Academy Press, Washington, D.C., 1988, p. 7.

Chapter 3

Deficiencies Exist in NASA's Oversight and Management of Tape Archiving and Storage Activities

NASA's magnetic tapes are neglected. As discussed in chapter 2, facilities storing NASA's tapes are not complying with tape management standards and are failing to ensure that magnetic tapes containing valuable data are adequately preserved.

During the past three decades, NASA did not give adequate attention to the archiving and storage of its space science data. At best, NASA addressed the growing volumes of stored data and related tape storage and archival problems in a piecemeal fashion, and in general, has not acted on many recommendations put forward by CODMAC and other scientific advisory groups.

We attribute these deficiencies to a lack of (1) management attention and participation in tape management and storage activities, (2) oversight by NASA's information resources management officials and responsible federal agencies, and (3) adequate funding for tape storage and archiving.

Data Management Is Treated as a Low Priority Activity

In the past, NASA viewed data management and data archiving as a low visibility, low priority activity. Traditionally, the planning, development, and management of new missions consumed the bulk of NASA's resources; the storage and archival of data acquired by past missions was given only scant attention and meager resources. A recent CODMAC report also addressed this issue:

> "While the collection of data from space attracts much interest, the more mundane issues of handling, managing, and disseminating these data are given less than adequate attention. The accumulation of data continues as do the data management problems with the loss of valuable data and with the difficulty of providing access to the data."[1]

NASA's Office of Space Science and Applications, which has overall responsibility for managing NASA's space science data, did not adequately lead and manage projects, field centers, and facilities managing, storing, and archiving data. We believe this lack of attention to data management issues is partially responsible for the poorly defined management structure, which was noted in a 1986 CODMAC report. The report notes that NASA's data management is fragmented and poorly coordinated, and recommends that:

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[1] Ibid., pp. 6-7

> **"There should be explicit, clearly understood assignment within NASA of responsibilities for computation and data management functions to specific offices and individuals. Since the overall responsibility for the effectiveness and productivity of the science and applications programs rests with the Associate Administrator for Space Science and Applications, that individual should take lead in ensuring that the various functions are clearly defined, and that responsibilities are unambiguously assigned as necessary to accomplish this task."[2]**

Lack of Management Oversight

NARA and GSA are responsible for periodic inspections of record and tape management practices of federal agencies.[3] Moreover, NASA's Information Resources Management (IRM) official is also responsible for ensuring that all facilities comply with NARA's regulations. However, we found that NASA's management of data has not been reviewed by either NARA or GSA, nor has it been reviewed by the Assistant Associate Administrator for IRM, NASA's Office of Management. Further, neither NARA, GSA, nor NASA's IRM officials have recently inspected or reviewed NASA's tape storage facilities or reviewed NASA's tape management and storage practices.

NASA's IRM Office Has Not Provided Adequate Oversight of Space Science Data Management

NASA's Assistant Associate Administrator for Information Resources Management, as the designated senior IRM official, is responsible for establishing agency policies for managing information processing resources and ensuring agency compliance with the applicable laws and regulations. NASA's IRM office is also responsible for oversight reviews of NASA's field centers, offices, and projects to determine compliance with mandatory information processing regulations, directives, and standards. Despite these responsibilities, the IRM office has not overseen NASA's management of its data holdings, because, according to the Director of NASA's IRM Policy division, the records management function was transferred to this office less than 4 years ago, in May 1986.

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[2] Issues and Recommendations Associated With Distributed Computation and Data Management Systems for the Space Sciences, Committee on Data Management and Computation, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council, National Academy Press, Washington, D.C., 1986, p. 106.

[3] Under section 2904 of Title 44, United States Code, NARA and GSA must oversee records management programs operated by federal agencies.

NARA Has Not Reviewed NASA's Records Management Activities

NARA is responsible for the inspection and evaluation of agency records management programs. The objectives[4] of NARA's inspections are to:

- determine agency compliance with NARA's records management regulations; and
- evaluate the effectiveness of agency records management programs and practices relating to adequacy of documentation, maintenance and use, and records disposition.

NARA has never inspected NASA's records management program. According to the Assistant Archivist for Management and Administration, NARA lacks the resources to perform more than two reviews annually. However, a NARA representative told us they worked in other ways with NASA regarding their records' management activities. For example, it is evaluating a revision to NASA's records disposition schedule. In addition, several years ago NARA established a task force to develop appraisal criteria for NASA's records. The task force visited five facilities and three federal records centers, reviewed seven space science projects, and issued a report summarizing its findings.[5] Although the report addressed several records management issues, it did not address NASA's compliance with federal tape management regulations, nor did it identify the deficiencies in tape management and storage practices that we found during our review.

GSA Oversight of NASA's Record Management and IRM Activities Is Inadequate

GSA is responsible for inspecting and evaluating agency record management programs.[6] These inspections should ensure that every agency complies with NARA and GSA regulations, and that each economically and effectively manages its records.

GSA did not perform the mandated reviews of NASA's tape management practices nor did it review its IRM activities. According to the Deputy Director of NASA's IRM Policy Division, GSA has never reviewed NASA's IRM or records management and tape storage activities, such as visiting tape storage facilities to ensure their compliance with applicable tape management standards. Although officials from GSA's Office of Information Resource Management could not explain GSA's failure, they said it is planning to strengthen its oversight and schedule agency reviews every 3 years. They also told us that GSA will, in January-March 1990, review NASA's information resources acquisition practices, and that the reviewers will be informed of our findings.

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[4] Code of Federal Regulations, Title 36, Subpart C - Agency Program Evaluation, Paragraph 1220.50, Evaluation by NARA

[5] Saving the Right Stuff, NARA, August 1986

[6] Code of Federal Regulations, Title 41, Chapter 201, Part 201-22, Records Management Program, Paragraph 201-22.001-4, GSA Responsibilities

Inadequate Funding for Data Archiving

The vast majority of funding for data storage is done on a mission-by-mission basis. Each mission is funded in two phases: (1) mission development and (2) mission operations and data analysis. The mission operations and data analysis phase includes funding for data processing, analysis, and storage. NASA and JPL officials told us that NASA usually underfunds the second phase and often uses those funds to cover first phase overruns. In addition, second phase funding for data storage assumes that most raw and intermediate data will be destroyed after it is processed, as required by NASA's regulations. However, organizations or scientists responsible for data are reluctant to destroy data they believe are potentially valuable. Instead, they store them in substandard conditions.

In addition to the mission-specific funding of data analysis and storage, NASA also funds NSSDC's long-term data storage and archiving. NSSDC, which is responsible for archiving data from all NASA's space science missions, and from selected NOAA, Department of Defense and international missions, had a 1989 budget of $3.2 million. This amount includes all its principal activities: data acquisition, processing, archiving, and distribution.

According to NASA and JPL officials in data management and archiving, data archiving and storage are often underfunded. CODMAC concurred and recommended that NASA establish a budget providing balanced support not only for instrument development, flight support, and immediate post-launch data handling, but also "... for the information processing, exchange, analysis, archiving, and other related activities."[7]

In effect, the report noted that NASA should allocate additional resources to manage and archive space science data so that these resources are commensurate with those for the development, launch, and operation of space science missions.

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[7] Issues and Recommendations Associated With Distributed Computation and Data Management Systems for the Space Sciences, Committee on Data Management and Computation, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council, National Academy Press, Washington, D.C., 1986, p. 104.

A NASA official responsible for the planning and coordinating the data management and archiving told us that although NASA needs more resources, including funds and personnel, it must also balance these requirements against available resources and the needs of other programs.

NASA's Efforts to Strengthen Its Data Management

NASA recognizes that a significant effort will be required to correct existing data management problems. Besides the data restoration projects discussed in chapter 2, it is taking several steps to correct existing problems and to prepare for the data expected to be generated by its future missions. These steps include

- establishing a task force to reassess NASA's management of data;
- using optical disk technology to archive selected data;
- developing a Master Data Directory with information on the location of data with significant scientific value; and
- initiating a census of space science data stored at JPL and Goddard.

Data Management Task Force

To strengthen data management and oversight and to develop a coherent data management plan, the Office of Space Science and Applications and the Office of Space Operations established a joint task force in July 1988 to identify data management problems and prepare an information systems management plan by November 1989. The scope of the task force's charge includes the evaluation of:

> "... full range of activities required to accomplish first-class scientific research... areas to be addressed are, flight data systems; experiment operations, including planning, scheduling and control; computer networking; computational systems; and data archival."

The task force's products are to include cost scenarios for different data management options, a draft of a new NASA data management policy, and an information system strategic plan. We met with task force staff and discussed the task force's activities and plans. Because they had not yet completed their work, it was too early to assess how the task force will influence NASA's management of its past and future data holdings.

Use of Optical Disk Technology

NASA is experimenting with advanced data storage technology and has established several projects using optical disks to store selected data. For example, at Goddard, one project is converting 10,000 tapes containing data from the Dynamic Explorer I and II to 243 optical disks, while another project implemented by NSSDC is using optical disks to store selected archival data. Similarly, JPL is using optical disks to store and disseminate planetary images obtained by NASA's deep space missions. While optical disk technology may offer improvements in NASA's data storage, archival, and dissemination, it is too early to assess its overall impact.

NASA's Master Data Directory

NSSDC is developing a NASA Master Directory, an on-line data search system designed to link users with existing data systems implemented by NASA and other federal agencies. In some cases, the directory provides an automatic network connection to data catalogs or information systems where more detailed information about data of interest may be found. According to NSSDC, the user may search for data by categories of interest such as science discipline, instrument, missions, or spatial coverage. The information displayed by the directory includes a descriptive title, summary abstract, key references, persons to contact, and storage media information.

Although the Master Directory is limited to data catalogs and data descriptions provided by the existing systems, other data of interest are being identified. NSSDC is planning to hire several scientists to identify additional data of significant scientific interest. According to its manager, the Directory project does not have the resources to identify all existing data of potential interest or their location. To obtain detailed information about the extent of all its data, NASA would have to perform a full-scale, comprehensive inventory and assessment of its data holdings.

Data Census

In August 1989, the Communications Division of the Office of Space Science and Applications initiated a NASA-wide census of data. Its purpose is to identify all NASA's data sets and thus to develop a "comprehensive picture of just what constitutes the NASA data base." The project is closely related to other activities, including tape restoration and the development of an archiving cost model. NASA is also planning to use the census information as input to its Master Directory project. Although the stated goal of the project is to inventory all NASA tape holdings, the first phase of the data census is limited to tape holdings maintained by

JPL and by Goddard. Because the project staff had not completed planning at the time of our review, it was too early for us to determine whether this effort will produce a comprehensive inventory of all NASA's data stored by NASA's centers, contract facilities, universities, individual scientists, and other federal agencies.

Chapter 4

Conclusions and Recommendations

Conclusions

NASA's management of data acquired by past space research and exploration missions is plagued by serious problems, with hundreds of thousands of magnetic tapes with long-term scientific value improperly stored and inadequately maintained. Valuable data from past missions are stored on deteriorating magnetic tapes and some irreplaceable data sets may have been lost. Since NASA does not have an agencywide inventory of its data, it does not know what is being retained and where it is located.

Data management and data archiving have received little attention from NASA officials responsible for the management of the nation's space research and exploration. In the past, NASA responded to needs of the scientific community to push the frontiers of space exploration by emphasizing new missions designed to carry advanced instruments into Earth orbit and to other planets of our solar system. While this emphasis dramatically expanded scientific knowledge and ensured that the United States established and maintained its pioneering role in many important aspects of space exploration, we believe that this success was partially achieved at the expense of preserving NASA's data holdings acquired by past missions.

The potential scientific value of these data holdings is unquestionable, and NASA has started to take steps to preserve some of its existing data holdings and is evaluating its data management structures and activities. However, NASA should do more.

First, NASA's data management and archival activities have to be elevated to a position of importance equal to that held by mission development and operations. Second, given NASA's decentralized structure and its decentralized management of its space science missions, a focused organizational structure is needed with clearly defined authority and responsibility. Third, NASA must determine the amount, location, and scientific value of its data. Without an agencywide inventory, NASA cannot adequately plan or budget for space science data management. Fourth, all valuable data should be made readily accessible to scientists either through a central data directory or by other means. Finally, NASA needs to allocate adequate funds and staff to data archiving to ensure that its data are adequately maintained and stored.

These steps will require considerable effort, different funding priorities, and a dramatic change in NASA's mission-oriented culture, which emphasizes development, launch, and operation of spacecraft and views data management as a low priority activity. Without a major effort to strengthen the management and archiving of NASA's data, and the allocation of necessary resources, valuable data will be lost. Furthermore, if NASA does not take the required steps to correct the existing deficiencies in its data management and archival operations, several of which have been known for the past decade, future missions will also be placed at risk, particularly if they rely on magnetic tapes as a primary data storage medium.

Clearly NASA must accept the major responsibility for the deplorable conditions under which scientific data are stored and maintained. Two organizations, NARA and GSA, have also not met their oversight responsibilities which, if properly exercised, could have brought the necessary attention and focus to have prevented or mitigated these problems.

Recommendations

Recommendations to the NASA Administrator

We recommend that the Administrator instruct NASA officials responsible for the management of data to:

- conduct a thorough inventory of all NASA's space science data stored at NASA centers and contractors, universities, research institutions, and other federal agencies;
- assess, in cooperation with the scientific community, the inventoried data for its scientific value and the integrity of its storage media;
- copy valuable data from deteriorating tapes to archival quality magnetic tapes or other storage media suitable for long-term retention of digital data, and release unneeded tapes for reuse or disposal;
- archive valuable scientific data in facilities that meet NARA regulations;
- develop and implement agencywide tape management and maintenance standards which include all NARA regulations and appropriate NIST guidelines;
- ensure that the offices and officials responsible for managing space science data are identified and their responsibilities clearly defined;
- ensure that NASA officials responsible for overseeing NASA's IRM periodically review NASA's data management and archiving to ensure compliance with NARA regulations; and
- ensure that NASA's data management and archiving are allocated adequate resources to properly store and maintain NASA's space science data holdings.

Recommendation to the GSA Administrator

We recommend that the Administrator periodically review and inspect NASA's records management practices as required by the Federal Information Resources Management Regulations.

Recommendation to the Archivist of the United States

We recommend that the Archivist periodically inspect and review NASA's records documentation and disposition practices as required by regulations.

Agency Comments and Our Evaluation

Commenting on a draft of our report, NASA contended it was safeguarding space science data as a national resource for future generations, but recognized room for improvement. It said it was addressing GAO's recommendations in ongoing or planned programs. Several of NASA's ongoing programs, including tape inventory and data restoration, are discussed in our report. Although these activities have been limited, NASA representatives told us they would be expanded in the future. Because NASA's detailed plans for implementing our other recommendations were still evolving when we finished our work, they could not be evaluated.

NASA expressed concerns that our report, while addressing what it termed "certain shortcomings in magnetic tape management," did not present a fair and balanced description of its efforts to manage space science data in a broader context. We disagree. As stated on page 48, our work focused on determining if NASA was adequately managing and archiving data from its past missions, which is now stored on magnetic tapes. In addition to fairly describing, and in most cases photographing, the conditions observed at 10 locations, we mentioned a number of instances where NASA is taking positive steps to address certain aspects of the tape storage and management problems (see pp. 31-33 and 40-42).

NASA also stated the report's tone was unnecessarily harsh, and that it contained sweeping generalizations that were unfounded and unsubstantiated. We disagree. Contrary to NASA's contentions, we believe our report fairly describes NASA's management of space science data holdings from past missions. Further, we think the seriously flawed conditions under which hundreds of thousands of tapes from past missions are stored, combined with the low priority accorded this important activity, unquestionably substantiate our conclusions and recommendations. Unless NASA addresses the serious tape management and storage problems noted, data from past missions will in fact be lost to future generations. NASA's letter and our evaluation of the comments it made on a draft of the executive summary are in appendix IV.

GSA and NARA also commented on our report. GSA reported it had strengthened its management oversight function and planned to conduct a review of NASA in early 1990. (See app. V.) NARA concurred that data management was a low priority in NASA, and believed this applied to records management as well. NARA believes that while NASA records managers are aware of tape management regulations, they have not been effectively communicated to NASA program managers. NARA supported our recommendation that NASA conduct an inventory of its data tapes, but stated that in the past NASA had refused to do so. NARA said it had not inspected NASA because of the massiveness of the undertaking, requirements in other areas, and an expectation that records management activities would improve based on other working relationships established during the past 5 years. NARA agreed, however, to consider inspecting NASA, but not before fiscal year 1991. NARA also made several comments about the way we rated its storage facilities. NARA's letter and our evaluation of its comments are in appendix VI.

Appendix I

Objectives, Scope, and Methodology

On November 10, 1988, the House Committee on Science, Space, and Technology asked us to report on whether NASA is (1) adequately managing and archiving space science data from its past missions stored on magnetic tapes, and (2) whether a mechanism exists for obtaining input from the scientific community on what types of space science data should be preserved and archived. This report addresses the first question; a subsequent report will address the second.

To answer the first question, we:

- identified federal and private sector tape management regulations and guidelines and developed a tape management checklist to review NASA's tape storage practices based on 11 factors developed from NARA regulations, and NIST and private sector guidelines;
- reviewed NASA's policies and guidelines governing the management of data;
- reviewed reports and documents related to the management of data, including reports prepared by NASA, CODMAC, and various scientific groups and committees;
- interviewed NASA and JPL officials responsible for managing NASA's data;
- interviewed NARA and GSA officials responsible for overseeing NASA's data management;
- identified and reviewed tape management practices at 10 data processing and storage facilities using a tape management checklist (see table 2.1); and
- discussed NASA's tape management practices with GSA and NARA officials.

We used NARA regulations and NIST guidelines as the primary guide in developing our tape management checklist. We supplemented our checklist with guidance provided by major manufacturers of magnetic computer tapes, as well as the International Council on Archives.

To determine the extent to which each facility complied with the regulations and guidelines, we:

- used our checklist to discuss, observe, and document the conditions found at each location, always in the presence of facility representatives;
- photographed examples of the conditions noted or used photographs provided by the facility; and
- modified, where appropriate, the results of our visits, based on written comments provided by each facility (discussed in app. III).

We also talked to the National Oceanic and Atmospheric Administration and to the United States Geological Survey officials for a broad perspective on tape management activities in other federal agencies.

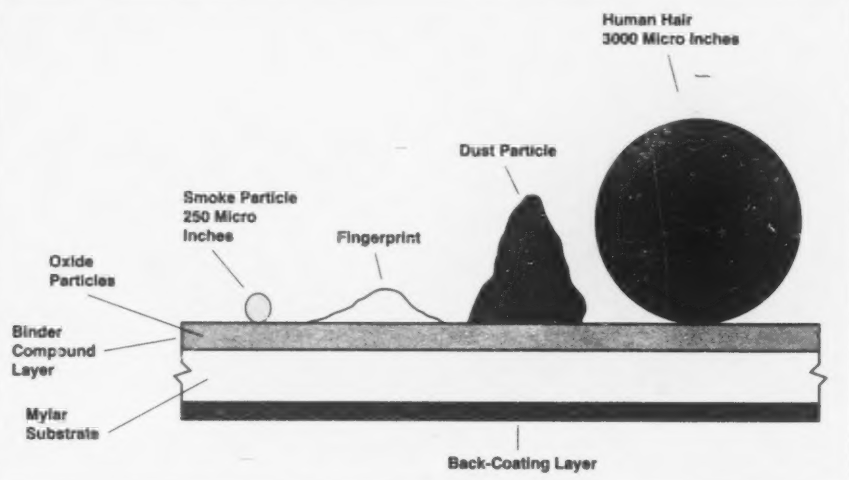
Our audit work was performed in accordance with generally accepted government auditing standards between November 1988 and January 1990 at various locations, including:

- NASA headquarters in Washington, D.C.;
- Goddard in Greenbelt, Maryland;
- NARA headquarters in Washington, D.C.;
- GSA headquarters in Washington, D.C.;
- National Oceanic and Atmospheric Administration's National Environmental Satellite, Data, and Information Service in Washington, D.C.;
- United States Geological Survey headquarters in Reston, Virginia;
- NIST headquarters in Gaithersburg, Maryland; and
- JPL in Pasadena, California.

Characteristics of Magnetic Tapes

A standard magnetic tape[1] consists of 2,400 feet of a thin substrate material, usually polyester film, coated with an iron oxide suspended in a binder. Other components include plasticizer, antistatic and wetting agents, lubricants, and agents designed to retard bloom and fungal growth. Figure II.1 shows the principal components of a magnetic tape in relationship with common contaminants. Figure II.2 is an electron microscope view of a foreign particle embedded in the binder of a magnetic tape.

Figure II.1: Magnetic Tape and Its Principal Contaminants[2]


Human Hair
3000 Micro Inches
Dust Particle
Smoke Particle
250 Micro
Inches
Fingerprint
Oxide
Particles
Binder
Compound
Layer
Mylar
Substrate
Back-Coating Layer

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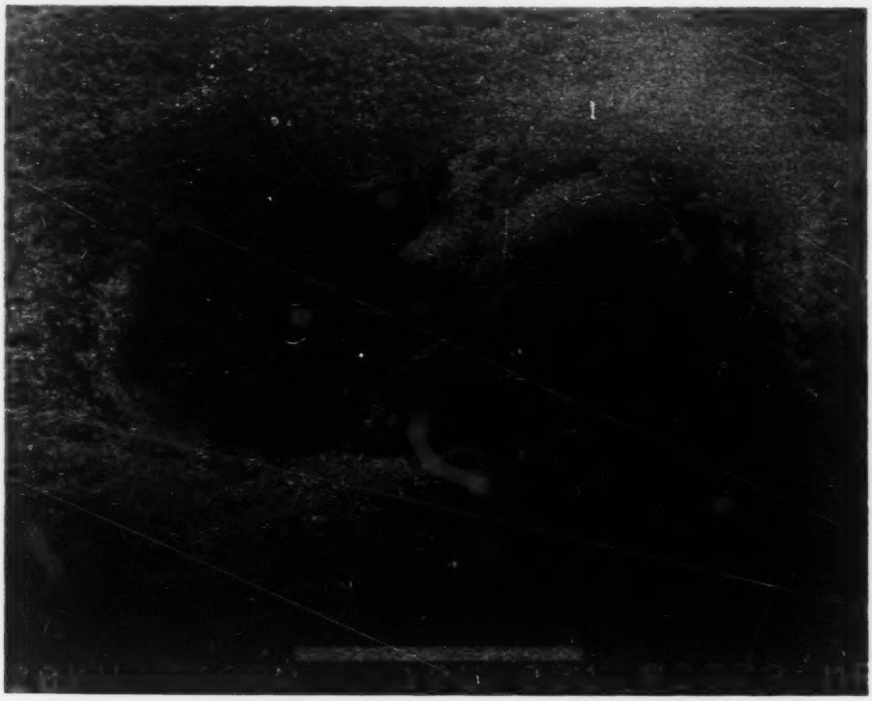
[1] In this report we are limiting our discussions to the most commonly used tape - the 2,400 feet long 6,250 Bits Per Inch (BPI) tapes. In addition to this type of tape, NASA is also using and storing a wide variety of tapes ranging from older, low density tapes to high density analog tapes.

[2] "Care and Handling Manual for Magnetic Tape Recording," in Magnetic Tape Recording for the Eighties, NASA Reference Publication 1075, NASA, April 1982, p. 133; and Tape Management and Evaluation, Data Devices International, Chatsworth, CA, 1982, p.10.

Figure II.2: Foreign Particle Embedded in Magnetic Tape[3]



A standard tape, consisting of polyester substrate coated with binder and magnetic oxide, is wound around a tape hub and sandwiched between two flanges. In some instances, the flanges are secured by a strap or a wrap-around band and hung on a tape rack. In other instances, tape may be stored in a plastic or metal canister.

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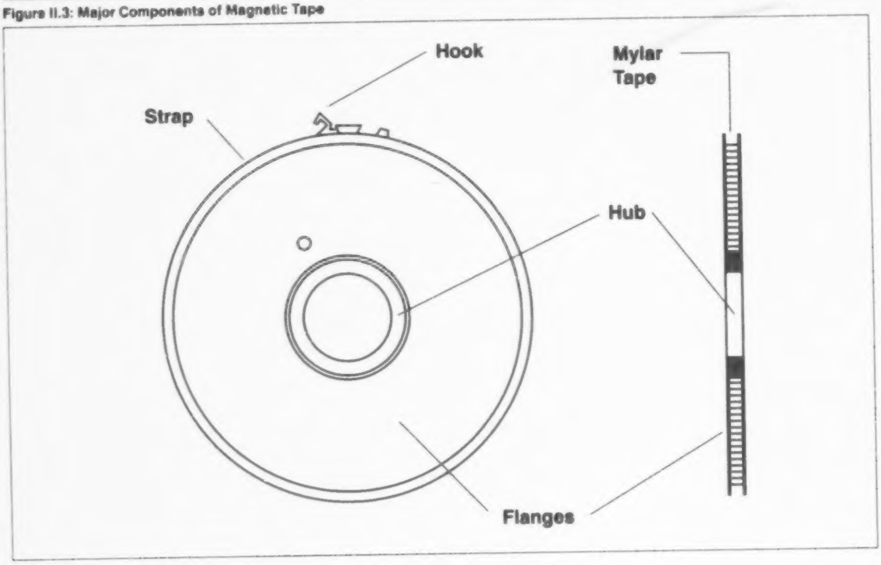
[3] Tape Management and Evaluation, Data Devices International, Chatsworth, CA, 1982, p. 7. (Courtesy of Data Devices International.)

Figure II.3: Major Components of Magnetic Tape



Facility Compliance With Tape Management Standards

Our review of selected tape processing and storage facilities revealed significant deficiencies in most aspects of the tape management process. Our findings are grouped by two sets of standards—NARA's mandatory regulations and NIST's and industry guidelines, including recommendations provided by the International Council on Archives. Our rating of facility compliance with tape management regulations and guidelines is based on visits to each facility, discussions with facility staff, and on a review of relevant documents. When appropriate, we photographed significant deficiencies in tape management practices and summarized our findings in a tape management checklist.

Response to Our Findings

We asked each facility[1] to review and comment on our findings. To facilitate this process, we gave them (1) a copy of our checklist including notations of the facility's compliance level, (2) a table including an explanation of how we assigned compliance ratings, (3) a copy of NARA's tape management regulations, and (4) a copy of NIST's tape management guidelines. We modified our rating in instances where the facility provided additional information or explanation. The following section summarizes their comments.

National Space Science Data Center

The Center's official agreed in general that NSSDC does not comply with all federal regulations and guidelines and noted that the facility was built 20 years ago, before these regulations were issued. He also stated that the facility "adopted" NIST's tape management guidelines which are implemented as resources permit. In regard to the uncalibrated temperature and humidity recorder installed in the NSSDC's tape library, the official said that there is no reason to believe that the temperature of the archive area has ever exceeded the recommended range. In responding to our finding on the lack of security, the official noted that NSSDC has never lost a tape through unauthorized removal or for any other reason. We were told that the Center is planning to redefine procedures and readjust spending priorities there and at NASA's headquarters to comply more fully with relevant federal regulations and guidelines. The Center said it is very concerned that NASA's data, acquired at significant cost to the U.S. taxpayer, will be available to tomorrow's researchers to further increase our understanding of our earth, solar system, and the universe.

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[1] We did not ask the Digital Equipment Corporation's Data Protection Services to comment because it is no longer operational. JPL transferred its tape holdings to another commercial facility.

We disagree with the Center's argument that its tapes are adequately stored. The Center is storing over 70,000 tapes in boxes at the Washington National Records Center with only partial environmental control and maintenance. Moreover, since the Center is not annually sampling its tape holdings, it cannot detect potential data losses. Similarly, while the lack of security at NSSDC's tape library may not have resulted in a documented unauthorized removal of stored tapes, this may occur unless the Center complies with NARA's access control regulations.

Smithsonian Astrophysical Observatory

Without commenting directly on our compliance ratings, the Observatory addressed several of our concerns. It noted that it (1) maintains a backup of tapes containing all intermediate and archival data, (2) regularly "spins" its tapes to prevent print-through, (3) plans to store and archive all its data on Write Once Read Many (WORM) and on Compact Disk Read Only Memory (CD-ROM) optical storage disks, and (4) plans to archive all original tapes at the NSSDC. Concerning the lack of security in the observatory's computer room and tape libraries, the official said that the nature of the data and the institution's research orientation do not warrant extraordinary access controls. NARA requires that only authorized personnel be given access to tape storage libraries and computer rooms. But we think an adequate access control may be implemented in a research setting without unduly burdening the users.

While the Observatory is maintaining backup of its tapes, many are with the originals. NARA requires that backup tapes be stored off-site to ensure their survival if the originals are destroyed. However, since the Observatory stored at least a part of its backup tapes off-site, we changed the backup rating from noncompliance to partial compliance.

Multi-Mission Image Processing Laboratory

No response received as of January 1990.

Infrared Processing and Analysis Center

The Center's official generally agreed with our findings and noted that the Center is planning to modify its practices to better comply with the relevant federal regulations and guidelines. As to the lack of security, the official partially disagreed with our findings, noting that all Center personnel are authorized to enter computer rooms and tape libraries, and that the introduction of a stringent access control may be counterproductive in a research environment. Nevertheless, NARA requires that facilities that store and process magnetic tapes implement adequate access controls to ensure that only authorized personnel are allowed to enter storage libraries and computer rooms.

Center for Astrophysics and Space Sciences

The Center disagreed with us about its tape management practices, noting that the findings distort the Center's tape storage activities. In particular, the official noted that (1) most of the data in the Center's archive and all the data in storage are from programs that closed, and the university holds no obligation or responsibility to the government for these data; (2) until GAO's review, the government was entirely indifferent to the data and has never funded their preservation. These data were kept because the Center's scientists believe that they have a potential scientific value; and (3) tapes containing data for which the Center is responsible are kept in an air conditioned building with temperature range between 60 and 75 degrees Fahrenheit.

While we agree that the Center may not have an obligation or responsibility to maintain data from NASA's older missions, the Center's scientists believe that these data have potential scientific value and should be preserved. Therefore, in our opinion, if these tapes contain valuable scientific data, then NASA and the Center must ensure that they are adequately maintained and stored. The Center also noted that NASA did not inform the Center that it should comply with federal tape management regulations and guidelines.

EROS Data Center

Generally agreeing with our compliance ratings, the Center noted its funding is inadequate to comply with every federal tape management regulation and guideline. The tape storage and maintenance problems will be solved once the Center transfers its tape holdings to optical disks. The Center stated that it is not cost-effective to maintain a duplicate set of the Center's tape holding in an off-site location, since its fire suppression system provides adequate protection for the stored tapes. While a good fire suppression system may limit damage, it is a NARA regulation to store a backup copy of all original tapes containing valuable data at an off-site location to ensure the preservation of data in the event of a major disaster.

Tape Staging and Storage Facility

Having agreed that TSSF does not comply with NARA temperature and humidity regulations, NASA monitoring officials noted their subsequent installation of a temperature and humidity record in the tape storage area. Agreeing that TSSF was in partial compliance with security regulations, he said it will post "authorized access only" signs at the entrance to the tape storage area. But this will not tighten the library's security. In regard to NIST's guidelines, the official responded that the facility will take corrective action when practical and if resources permit. Despite these deficiencies, he insisted the tapes have not been harmed. But having failed to sample and test stored tapes in accord with NARA's regulations, TSSF cannot possibly know if their tapes are unharmed. Until these deficiencies are corrected, they remain at risk.

We also found that TSSF was storing several hundred thousand tapes in boxes kept on pallets strapped by steel bands. The official noted that if the facility were to store these tapes on tape racks, the storage costs would be significantly higher, since the facility would require additional storage space. Granting his argument, the practice is nevertheless totally unacceptable and should be corrected.

National Archives and Records Administration

NARA stated that it has only a limited responsibility for NASA tapes stored at NARA's record centers. From NARA's perspective, as long as the tapes remain in NASA's legal custody, NASA is solely responsible for regulations such as tape cleaning, certifying, and backups. NARA also pointed out that NIST's guidelines were not incorporated in NARA's regulations and therefore are not applicable to NARA's Washington National Records Center and the Los Angeles National Records Center at Laguna Niguel. NARA's responses to our compliance ratings for both facilities are discussed below. We agree that NASA is responsible for the maintenance of its tapes stored at NARA's federal centers, and for that reason we did not rate NARA's compliance with such regulations in regards to its centers. However, we found that NARA records centers were not complying with NARA's own tape management regulations, and that NARA was also not providing oversight of NASA tape management practices despite its responsibility for doing so. While we agree that NARA is not required to implement NIST's tape management guidelines, we believe that following them would ensure the preservation of tapes stored at NARA's federal records centers.

Washington National Records Center

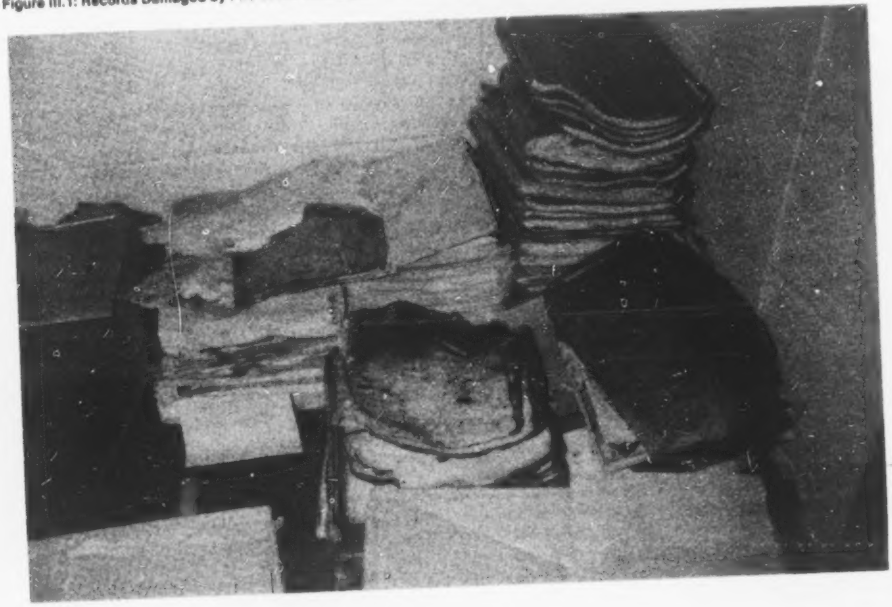
NARA did not fully concur with our compliance rating. Specifically, NARA noted that the Center:

- is in partial compliance with the temperature and humidity regulations in the storage vault holding NASA tapes by periodically measuring temperature and humidity with a portable hygro-thermograph; we agreed and adjusted our rating accordingly;

- is now in full compliance with the access control regulations since the Center has stationed a guard in the facility's lobby to monitor the front entrance and exits;
- is in full compliance with the fire protection regulations because of the Center's adherence to fire codes and regulations, which mitigates fire hazards posed by combustible materials stored near NASA tapes.

We disagree because, according to NIST, combustible materials nearby constitute a fire hazard. We pointed out that a fire did occur in one of the Center's vaults as shown in the following figure:

Figure III.1: Records Damaged by Fire at the Washington National Records Center



- is in full compliance with the water protection guidelines and provides plastic sheets in the event of a water leak. We disagree since full compliance in this category would require the installation of water detectors.

NARA also stated that because NASA's tapes are stored in boxes, the Center does not require tape racks. We disagree, since the practice of storing tapes in unsealed boxes rather than in tape racks is not recommended by either NIST or the industry.

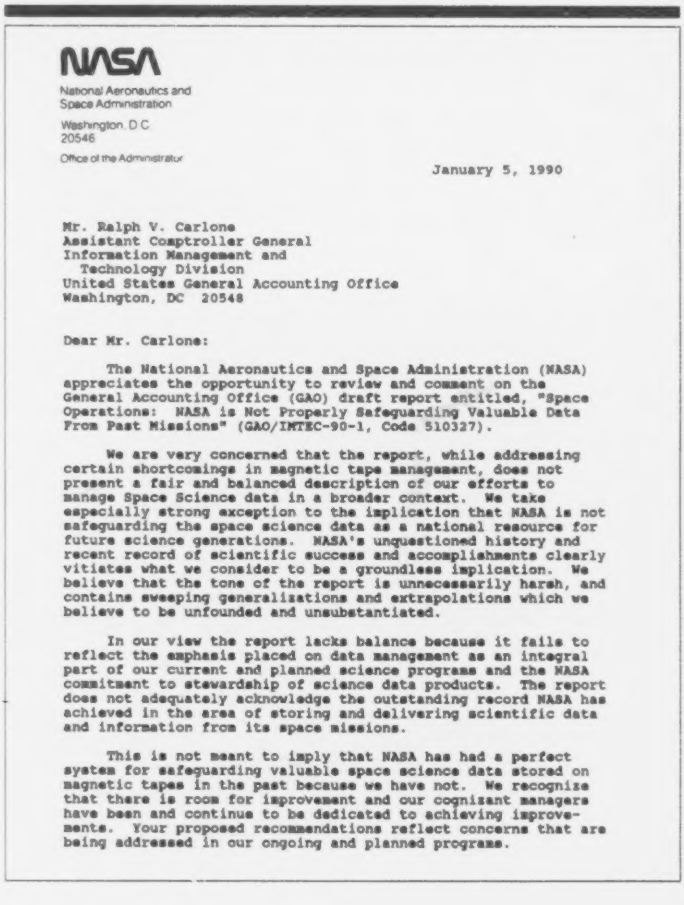
Federal Records Center, Laguna Niguel

NARA concurred with our rating for the temperature and humidity control, but disagreed with our rating for the fire and water protection guidelines, noting that the Center's storage area is adequately protected by an automatic sprinkler system. We disagree, because the Center did not install water detectors and was storing tapes in close proximity to combustible materials.

Appendix IV

NASA's Comments and GAO's Response

Note: GAO comments supplementing those in the report text appear at the end of this appendix.



NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

January 5, 1990

Mr. Ralph V. Carlone
Assistant Comptroller General
Information Management and
  Technology Division
United States General Accounting Office
Washington, DC 20548

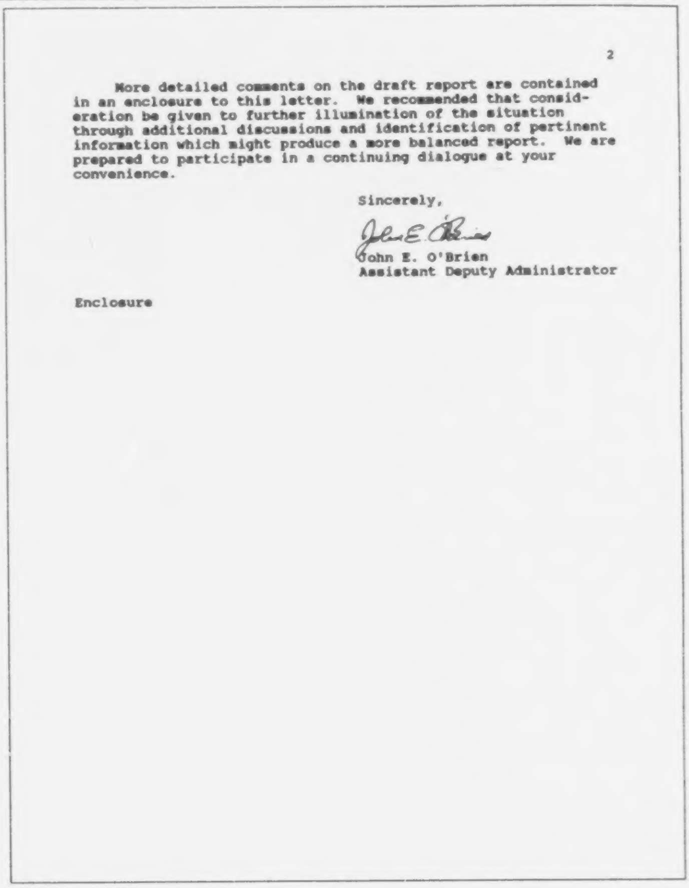
Dear Mr. Carlone:

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the General Accounting Office (GAO) draft report entitled, "Space Operations: NASA is Not Properly Safeguarding Valuable Data From Past Missions" (GAO/IMTEC-90-1, Code 510327).

We are very concerned that the report, while addressing certain shortcomings in magnetic tape management, does not present a fair and balanced description of our efforts to manage Space Science data in a broader context. We take especially strong exception to the implication that NASA is not safeguarding the space science data as a national resource for future science generations. NASA's unquestioned history and recent record of scientific success and accomplishments clearly vitiates what we consider to be a groundless implication. We believe that the tone of the report is unnecessarily harsh, and contains sweeping generalizations and extrapolations which we believe to be unfounded and unsubstantiated.

In our view the report lacks balance because it fails to reflect the emphasis placed on data management as an integral part of our current and planned science programs and the NASA commitment to stewardship of science data products. The report does not adequately acknowledge the outstanding record NASA has achieved in the area of storing and delivering scientific data and information from its space missions.

This is not meant to imply that NASA has had a perfect system for safeguarding valuable space science data stored on magnetic tapes in the past because we have not. We recognize that there is room for improvement and our cognizant managers have been and continue to be dedicated to achieving improvements. Your proposed recommendations reflect concerns that are being addressed in our ongoing and planned programs.

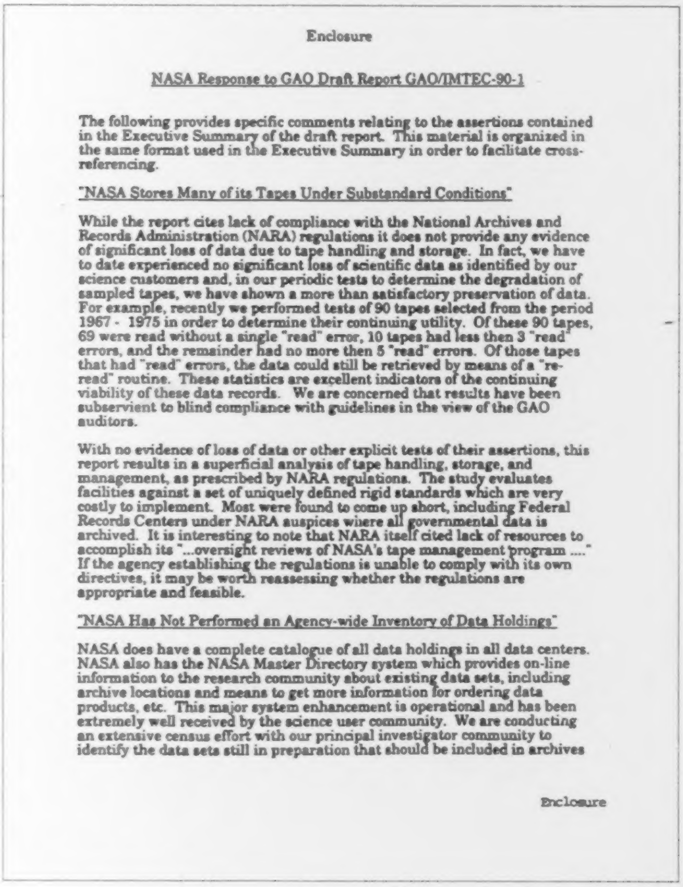


More detailed comments on the draft report are contained in an enclosure to this letter. We recommended that consideration be given to further illumination of the situation through additional discussions and identification of pertinent information which might produce a more balanced report. We are prepared to participate in a continuing dialogue at your convenience.

Sincerely,

John E. O'Brien
Assistant Deputy Administrator

Enclosure



Enclosure

NASA Response to GAO Draft Report GAO/IMTEC-90-1

The following provides specific comments relating to the assertions contained in the Executive Summary of the draft report. This material is organized in the same format used in the Executive Summary in order to facilitate cross-referencing.

"NASA Stores Many of its Tapes Under Substandard Conditions"

While the report cites lack of compliance with the National Archives and Records Administration (NARA) regulations it does not provide any evidence of significant loss of data due to tape handling and storage. In fact, we have to date experienced no significant loss of scientific data as identified by our science customers and, in our periodic tests to determine the degradation of sampled tapes, we have shown a more than satisfactory preservation of data. For example, recently we performed tests of 90 tapes selected from the period 1967 - 1975 in order to determine their continuing utility. Of these 90 tapes, 69 were read without a single "read" error, 10 tapes had less then 3 "read" errors, and the remainder had no more then 5 "read" errors. Of those tapes that had "read" errors, the data could still be retrieved by means of a "re-read" routine. These statistics are excellent indicators of the continuing viability of these data records. We are concerned that results have been subservient to blind compliance with guidelines in the view of the GAO auditors.

With no evidence of loss of data or other explicit tests of their assertions, this report results in a superficial analysis of tape handling, storage, and management, as prescribed by NARA regulations. The study evaluates facilities against a set of uniquely defined rigid standards which are very costly to implement. Most were found to come up short, including Federal Records Centers under NARA auspices where all governmental data is archived. It is interesting to note that NARA itself cited lack of resources to accomplish its "...oversight reviews of NASA's tape management program ...." If the agency establishing the regulations is unable to comply with its own directives, it may be worth reassessing whether the regulations are appropriate and feasible.

See comment 1

"NASA Has Not Performed an Agency-wide Inventory of Data Holdings"

NASA does have a complete catalogue of all data holdings in all data centers. NASA also has the NASA Master Directory system which provides on-line information to the research community about existing data sets, including archive locations and means to get more information for ordering data products, etc. This major system enhancement is operational and has been extremely well received by the science user community. We are conducting an extensive census effort with our principal investigator community to identify the data sets still in preparation that should be included in archives

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and made available to the general research community. As these data sets are identified, they will be added routinely to the NASA Master Directory to provide a complete and easily accessible reference for our entire community. This process was thoroughly described to the auditors during the course of the investigation, although not acknowledged in the Executive Summary of the report.

See comment 2

The assertion focuses on the mechanics of counts of magnetic tape reels, totally ignoring the essence of the NASA mission which is to manage and make available the data and information stored on that medium.

"Scarce Resources are Used to Store Data of Little or No Value"

The assertion that NASA is using scarce resources to store data that may be of little or no scientific value is without merit and, in light of the activities underway at the time of the audit, particularly troublesome. The example cited refers to 130,000 tapes stored at a federal records center. NASA had initiated and was performing an analysis in conjunction with representatives of the planetary science discipline to determine their scientific value before summarily destroying the total inventory. NASA feels that prior to any decision to dispose of this data, a reasonable effort to determine the value is warranted. This approach is in keeping with the primary objective of not dispensing any space-derived data set without a conscious professional assessment of its ultimate worth to the science community.

The accusation that a group of scientists noted that much of the planetary data archived by the NSSDC are of uncertain quality or accuracy becomes obsolete when one recognizes the time frame of the situation cited. The particular statement appeared in a report documenting a 1983 workshop. Since that time, we have implemented a Planetary Data System that provides electronic access to these data in order for the discipline researchers to perform their analyses. This telecommunications system provides ease of access to the data as it is being analysed and facilitates early recognition of any problems regarding data quality and accuracy before certification of a data set for inclusion in the archive system. We have also begun to implement a program whereby ongoing research is co-located with repositories of major data sets. This approach assures continuous evaluation of the data for their quality and utility for specific research investigations. The Infrared Processing and Analysis Center (IPAC) for astrophysics research is a model of this concept and is recognized by members of this discipline as a major contribution to the productivity of their research.

See comment 3

"Data Archiving is Treated as a Low Priority Activity"

We find this assertion to be particularly ironic in light of recent Congressional actions taken with the NASA budget. NASA has continuously sought to assure appropriate funding for the data archival function. In FY 1989, NASA was directed to absorb a $10M cut apportioned between information systems and commercial programs. We were able in that budget to limit the actual reduction for information systems to $2.5M. In FY 1990, the Associate Administrator for Space Science and Applications took the initiative to submit a budget that increased funding for archiving by $3M in

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FY 1990 and growing to over $5.0M in subsequent years. Final action by the Congress on the FY 1990 budget request was to direct a reduction of $5M in the overall information systems program.

Notwithstanding the statement by GAO that overall responsibility for data archiving has not been assigned, it is clear within NASA that management of our space-acquired data assets is assigned to the Office of Space Science and Applications (OSSA) These duties are accomplished within broad institutional policies and guidelines for information resources management provided by the Office of Management. The Communications and Information Systems Division has principal responsibility within OSSA for ensuring that science data are archived and made available to the general science community. This is accomplished in close conjunction with the science discipline divisions within OSSA where specific flight and research programs are implemented. A key element for implementing the archive program is the National Space Science Data Center which has been assigned since 1967 the responsibility for preserving project generated data.

Balancing our resources for data acquisition with those for data management and archiving is also a significant effort in the early planning and implementation of each of our new flight projects. Our "new start" cost reviews require that specific attention be given to addressing the resources required for ongoing data management. OSSA has implemented a NASA policy which requires that each flight project office generate a Project Data Management Plan (PDMP) which establishes detailed understanding of the expected data volume and characteristics, the data processing system design, and anticipated delivery schedules for archival data delivery.

The importance of long-term data management issues as a priority at the onset of a project is demonstrated by the Data Archival and Distribution System (DADS) for Hubble Space Telescope (HST) and the Data and Information System (DIS) for Earth Observing System (EOS) projects. In both examples, active forethought has been given to archival and distribution of data products of assured quality through the extended lifetime of their respective projects. The importance and criticality of science data handling to the success of the EOS mission is reflected by the fact that it represents one of the largest elements in overall program resource estimates.

In addition, OSSA has initiated an Information Systems Strategic Planning Project that has involved the space science research community as well as the Agency's operational elements to provide guidance on an appropriate approach to this overall function. The project report is in final preparation for publication and implementation has begun within OSSA as well in the Office of Space Operations.

See comment 4

"Recommendations"

As evidenced by NASA's recognition in the worldwide science community as the foremost leader in providing scientific results from its flight missions and subsequent analysis, we cannot accept the reference to "chronic deficiencies in NASA's management of the existing space science data." Our record demonstrates that we have created a system that is responsive to the needs

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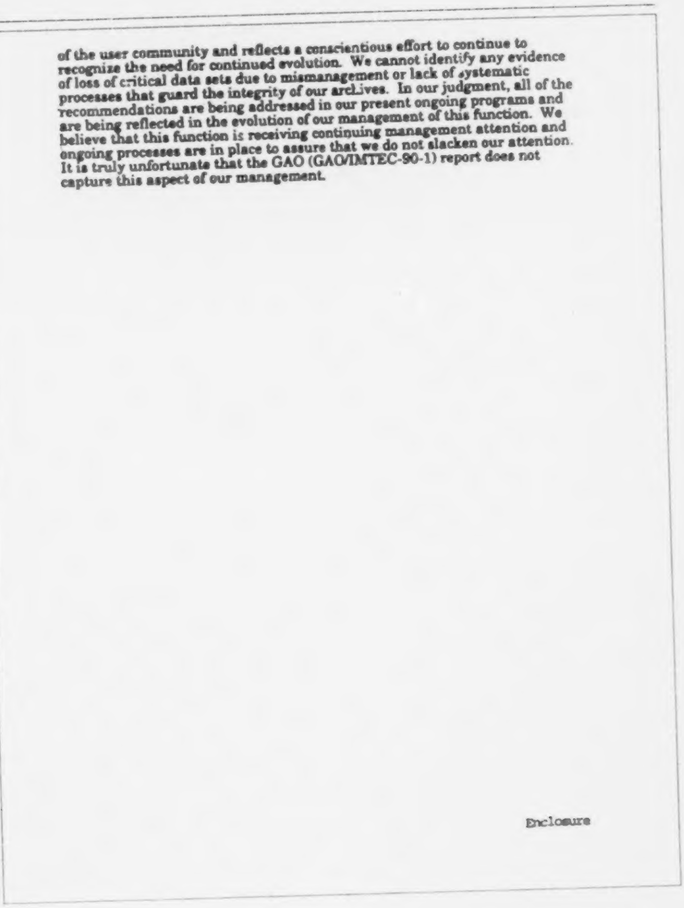
See comment 5



of the user community and reflects a conscientious effort to continue to recognize the need for continued evolution. We cannot identify any evidence of loss of critical data sets due to mismanagement or lack of systematic processes that guard the integrity of our archives. In our judgment, all of the recommendations are being addressed in our present ongoing programs and are being reflected in the evolution of our management of this function. We believe that this function is receiving continuing management attention and ongoing processes are in place to assure that we do not slacken our attention. It is truly unfortunate that the GAO (GAO/IMTEC-90-1) report does not capture this aspect of our management.

Enclosure

The following are GAO's comments on the National Aeronautics and Space Administration letter dated January 5, 1990. NASA limited its detailed comments to the draft executive summary of this report.

GAO Comments

1. "NASA Stores Many of its Tapes Under Substandard Conditions"

According to NASA, our report contains no evidence of any significant loss of data due to tape handling and storage, and its periodic tests to determine the degradation of sampled tapes show that it is satisfactorily preserving data. NASA says that with no evidence of loss of data or other explicit tests of our assertions, our report results in a superficial analysis of tape handling, storage, and management, as prescribed by NARA regulations. NASA also suggested that NARA may need to reassess whether its regulations are appropriate and feasible.

We disagree. First, we believe we have cited sufficient evidence of a major risk to NASA data. According to JPL officials with substantial experience and expertise in tape management and restoration, data have been lost. JPL estimates that about 50 percent of the 130,000 tapes it had originally stored at a federal records center may be damaged beyond recovery or contain data of little or no value. This evidence, combined with the serious physical storage conditions we noted elsewhere, substantiates our concern that NASA's space science data stored on magnetic tapes are at serious risk of becoming partially or completely unusable.

Second, NASA's assertion that its periodic testing of stored tapes provides excellent indicators of the continuing viability of its tapes is misleading. NASA's use of the word periodic implies that it has a regular ongoing program to monitor the condition of its tapes. Although NARA requires that each tape storage facility annually sample its tape holdings to detect tape deterioration, none of the facilities we visited performed the mandatory annual tests. Further, the test NASA referred to was a single test of 90 tapes, which is insufficient to detect tape deterioration and data losses because the sample NASA used was not statistically valid and represented only a small fraction of the 113,000 tapes stored by NSSDC. Therefore, the results cannot be projected to NSSDC's overall tape holdings, nor can they be projected to tape holdings maintained by NASA in other facilities. We considered performing actual tests for readability, but chose not to because of a very serious tape restoration problem discovered by JPL and the potential risk of losing NASA's valuable data. As explained on page 31, JPL found that trying to read tapes over 10 years old can often destroy them.

Third, regarding NARA's regulations, we believe that NASA had ample opportunity to challenge NARA's tape management regulations when they were published for comment in the Federal Register.[1] In commenting on the proposed revisions, NASA did not challenge two of the key tape management regulations—temperature and humidity control, and annual testing of stored tapes,[2] —and went further to suggest that the

> "requirement to maintain magnetic computer tapes at a constant temperature of 62-68° F and a constant relative humidity of 34-35% should apply to Federal records centers also, because all of them do not provide these conditions."

Also, NASA did not challenge NARA's regulation for annual sampling and testing of stored tapes to detect deterioration. In commenting on a regulation directing agencies to copy permanent data before the tapes are 10 years old on to tested and verified new tapes, NASA did argue that this regulation may be costly, but suggested that this regulation "should be determined by the annual 3 percent test results."

2. "NASA Has Not Performed an Agency-wide Inventory of Data Holdings"

NASA's position that each of its data centers has a complete catalogue of all data holdings and that its Master Directory provides on-line information to the research community does not negate our finding that NASA does not maintain a central inventory of its magnetic tapes containing space science data. First, while we noted that each facility we visited maintained a tape and data inventory, these inventories were of varying quality and completeness. Second, the NASA Master Directory does not keep information on individual magnetic tapes, but provides limited information about data sets in selected scientific disciplines. According to NASA officials, the directory contains approximately 1,000 data sets, thus representing only a small fraction of the existing space science data now stored on magnetic tapes.

NARA requires that each agency maintain a complete inventory of its magnetic tapes. This regulation is designed to provide information needed for the development of specific disposition instructions for data stored on tapes, including retention periods for temporary and permanent records. NARA officials noted that in the past NASA has refused to perform such an inventory, noting that NARA's inventory regulation was too "intrusive."

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[1] Federal Register (53 FR 48936), December 5, 1988.

[2] NASA's "Comments on Proposed Revision of Code of Federal Regulations, Title 36, Chapter 12, Part 1234, Electronic Record Management," February 6, 1989.

About October 1989, NASA launched a commendable effort to inventory its tapes. At the time we completed our work, this "census" effort was limited to tapes managed by Goddard and JPL. In January 1990, NASA told us it planned to expand this census to include additional locations, but gave no specific details on the scope of this effort. Chapter 3 details NASA's Master Directory and its ongoing tape census.

3. "Scarce Resources are Used to Store Data of Little or No Value"

This section, although now deleted from the executive summary, is discussed on pp. 33 to 34 of the report. NASA asserts that our finding is without merit, but we disagree. The evidence we used to support our concern that scarce resources may be used to store some tapes that may contain data of marginal value is based on information obtained at two locations—JPL and NSSDC. According to JPL officials familiar with its restoration efforts, about half of the 130,000 tapes formerly stored at the Federal Records Center were probably damaged or degraded beyond restoration, or contained data no longer worth keeping. Thus, about 65,000 tapes kept by JPL in storage contained data of little or no value or data that cannot be restored.

In regard to the variable quality, questionable accuracy, and low resolution of the planetary data archived by NSSDC, NASA comments that the statement made by the planetary scientists in 1983 is now obsolete since NASA has implemented the Planetary Data System that provides electronic access to these data so the discipline researchers can perform their analyses. This implies that (1) NASA has improved the quality, accuracy, and completeness of these data, and (2) these data were transferred from NSSDC and are currently resident in the Planetary Data System.

We disagree with these implications. According to its manager, the system incorporates only a fraction of these data. The system is restoring data from past planetary missions, and plans to incorporate them in its data base. But there is no schedule for completion of this effort, which, in any case, depends on funds NASA allocates.

Nonetheless, we did note on p. 34 that NASA has taken steps to strengthen its archiving of planetary data through the Planetary Data System. If the conditions noted in the planetary data also applied to data from other scientific disciplines, other tapes may contain data of marginal value.

4. "Data Archiving is Treated as a Low Priority Activity"

According to NASA, it has continuously sought to assure appropriate funding for the data archival function, but budget cuts in fiscal years 1989 and 1990 prevented it from doing so. The management of space-acquired data is assigned to the Office of Space Science and Applications, which, through project data management plans, requires new missions to specifically address the resources required for ongoing data management. Its commitment to long-term data management and preservation is demonstrated in the development of data systems designed to support new missions, including the Hubble Space Telescope and the Earth Observing System and by the Information System Strategic Planning Project.

We could not substantiate NASA's funding assertions for prior years, as well as fiscal years 1989 and 1990. Although Congress cut NASA's information systems budget both years, NASA officials could not document its plans to allocate additional resources to (1) improve its management of magnetic tapes containing space science data from its past missions beyond those resources allocated to the limited data restoration and data census activities, and (2) upgrade its tape storage facilities to conform with federal regulations.

We do not dispute that responsibility for data archiving is assigned to the Office of Space Science and Applications. Our point is that this office, for past missions, "did not adequately lead and manage projects, field centers, and facilities that manage, store, and archive data." In light of the deficiencies we noted during our visits to NASA's tape storage facilities, including the massive volumes of poorly maintained tapes stored in what NASA officials themselves described as "deplorable conditions," we could not conclude otherwise. Moreover, our concerns regarding the poorly defined management structure and responsibilities are also shared by NARA. In commenting on this report, the Archivist of the United States noted that, based on NARA's experience, our conclusion that NASA views data management as a low priority activity was not limited to data management, but also applied to records management as well.

We believe NASA's emphasis on ensuring that its new missions pay specific attention to the allocation of data management resources is a positive step that may help to ensure the preservation of valuable data from future missions. We applaud NASA's decision to require that each mission prepare a project data management plan. Yet, although this requirement was established in 1978, it has not been enforced. Not one NASA mission launched between 1978 and 1987 prepared such a plan.

We agree that new and sophisticated data management systems and strategies is another positive step in the long-term management and preservation of space science data to be acquired by the future missions. However, as evidenced by our findings, we did not find a similar commitment to the preservation of data acquired by the past missions.

5. "Recommendations"

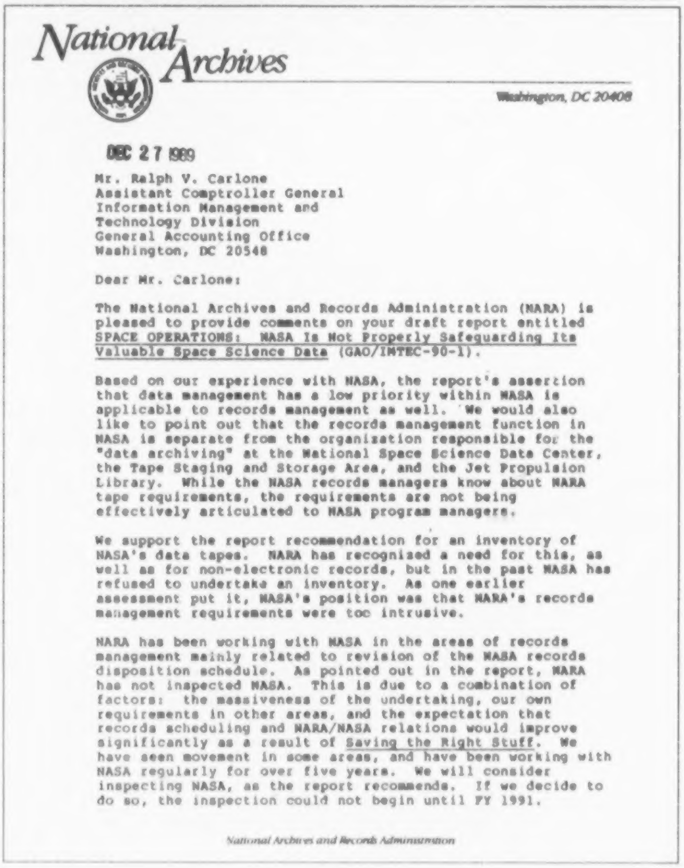
Citing its recognition in the worldwide science community as the foremost leader in providing scientific results from its missions, NASA cannot accept the reference to chronic deficiencies in its management of existing space science data. NASA notes that it cannot identify any evidence of loss of critical data sets due to mismanagement or a lack of systematic processes that guard the integrity of its archives. We disagree.

Although NASA appears to be heading in the right direction towards handling data from future missions, we do not believe the deficiencies in managing data from past missions occurred overnight. Beginning with early spacecraft, data began to accumulate. Although the problems may have been insignificant at first, NASA now has well over 1 million tapes that must be identified, maintained, and, where appropriate, preserved for future science generations. In light of the poor storage conditions we noted at several locations, combined with the lack of proper maintenance, we believe that NASA would find data losses if it complied with NARA's regulation and periodically sampled its tape holdings to detect tape and data deterioration. JPL's current restoration of the 130,000 tapes formerly stored at the Federal Records Center in Laguna Niguel substantiates our concerns and provides NASA with a wealth of information on the effects of a substandard tape storage environment on magnetic tapes and on the extent of data losses. We suggest that NASA use this information to develop programs designed to protect the hundreds of thousands of magnetic tapes stored without adequate environmental controls in other NASA and contractor tape storage facilities.

NASA stated that our recommendations were being addressed in its present ongoing programs and were being reflected in the evolution of its management of this function. While we agree that NASA is planning to partially implement two of our recommendations, it is too early to evaluate if these or other planned actions will be successful.

NARA's Comments and GAO's Response

Note: GAO comments supplementing those in the report text appear at the end of this appendix.



National Archives
Washington, DC 20408

DEC 27 1989

Mr. Ralph V. Carlone
Assistant Comptroller General
Information Management and
Technology Division
General Accounting Office
Washington, DC 20548

Dear Mr. Carlone:

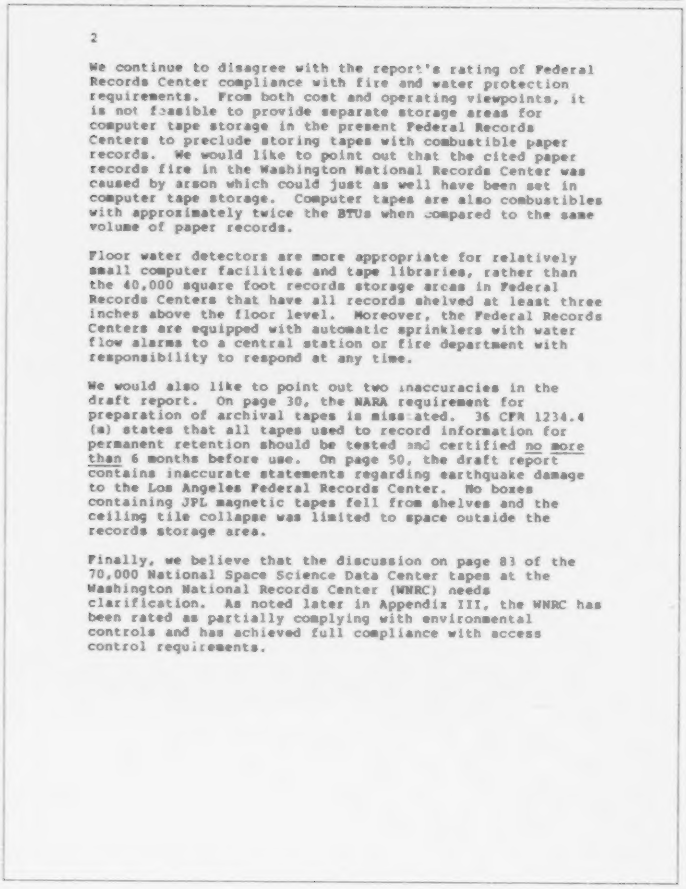
The National Archives and Records Administration (NARA) is pleased to provide comments on your draft report entitled SPACE OPERATIONS: NASA Is Not Properly Safeguarding Its Valuable Space Science Data (GAO/IMTEC-90-1).

Based on our experience with NASA, the report's assertion that data management has a low priority within NASA is applicable to records management as well. We would also like to point out that the records management function in NASA is separate from the organization responsible for the "data archiving" at the National Space Science Data Center, the Tape Staging and Storage Area, and the Jet Propulsion Library. While the NASA records managers know about NARA tape requirements, the requirements are not being effectively articulated to NASA program managers.

We support the report recommendation for an inventory of NASA's data tapes. NARA has recognized a need for this, as well as for non-electronic records, but in the past NASA has refused to undertake an inventory. As one earlier assessment put it, NASA's position was that NARA's records management requirements were too intrusive.

NARA has been working with NASA in the areas of records management mainly related to revision of the NASA records disposition schedule. As pointed out in the report, NARA has not inspected NASA. This is due to a combination of factors: the massiveness of the undertaking, our own requirements in other areas, and the expectation that records scheduling and NARA/NASA relations would improve significantly as a result of Saving the Right Stuff. We have seen movement in some areas, and have been working with NASA regularly for over five years. We will consider inspecting NASA, as the report recommends. If we decide to do so, the inspection could not begin until FY 1991.

National Archives and Records Administration



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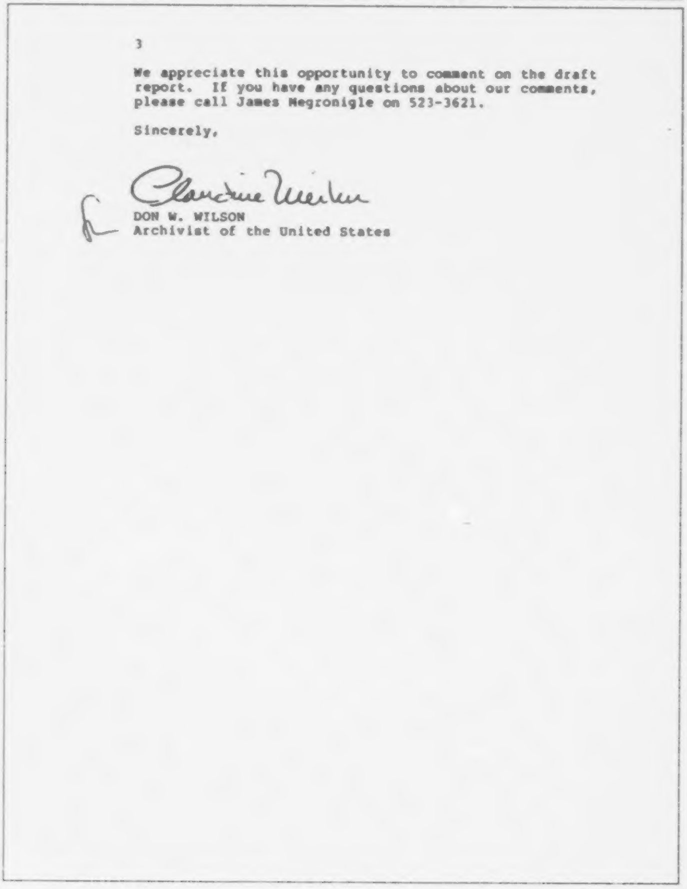
We continue to disagree with the report's rating of Federal Records Center compliance with fire and water protection requirements. From both cost and operating viewpoints, it is not feasible to provide separate storage areas for computer tape storage in the present Federal Records Centers to preclude storing tapes with combustible paper records. We would like to point out that the cited paper records fire in the Washington National Records Center was caused by arson which could just as well have been set in computer tape storage. Computer tapes are also combustibles with approximately twice the BTUs when compared to the same volume of paper records.

Floor water detectors are more appropriate for relatively small computer facilities and tape libraries, rather than the 40,000 square foot records storage areas in Federal Records Centers that have all records shelved at least three inches above the floor level. Moreover, the Federal Records Centers are equipped with automatic sprinklers with water flow alarms to a central station or fire department with responsibility to respond at any time.

We would also like to point out two inaccuracies in the draft report. On page 30, the NARA requirement for preparation of archival tapes is misstated. 36 CFR 1234.4 (a) states that all tapes used to record information for permanent retention should be tested and certified no more than 6 months before use. On page 50, the draft report contains inaccurate statements regarding earthquake damage to the Los Angeles Federal Records Center. No boxes containing JPL magnetic tapes fell from shelves and the ceiling tile collapse was limited to space outside the records storage area.

Finally, we believe that the discussion on page 83 of the 70,000 National Space Science Data Center tapes at the Washington National Records Center (WNRC) needs clarification. As noted later in Appendix III, the WNRC has been rated as partially complying with environmental controls and has achieved full compliance with access control requirements.



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We appreciate this opportunity to comment on the draft report. If you have any questions about our comments, please call James Megronigle on 523-3621.

Sincerely,

Claudine Weiher

DON W. WILSON
Archivist of the United States

The following are GAO's comments on the National Archives and Records Administration letter dated December 27, 1989.

GAO Comments

NARA disagreed with our findings that the Washington National Records Center and the Federal Records Center in Laguna Niguel are in partial compliance with fire and water protection guidelines, noting that (1) it is not feasible to provide separate storage areas for computer tapes, and (2) water detectors are more appropriate for relatively small computer facilities and tape libraries.

According to NIST and industry guidelines, magnetic tapes should not be stored together with large volumes of paper records, regardless of whether the storage areas are equipped with automatic fire sprinklers or not.

In regard to the two inaccuracies in the draft report identified by NARA (incorrect citation of NARA regulation and the extent of earthquake damage at the Federal Records Center in Laguna Niguel), we corrected the identified citation, but we disagree with NARA's assertion regarding the earthquake damage. In a memorandum prepared by JPL staff following their visit to the Federal Records Center in Laguna Niguel, the staff noted:

> "Visiting the area, we noted that the steel shelves, which are about eight feet tall and three feet wide, were moved two inches to the side, toppling several boxes of our tapes from the top shelf to the floor. We were told that many sections of the acoustical ceiling were shaken loose and fell onto the boxes of tapes, as well as the floor."[1]

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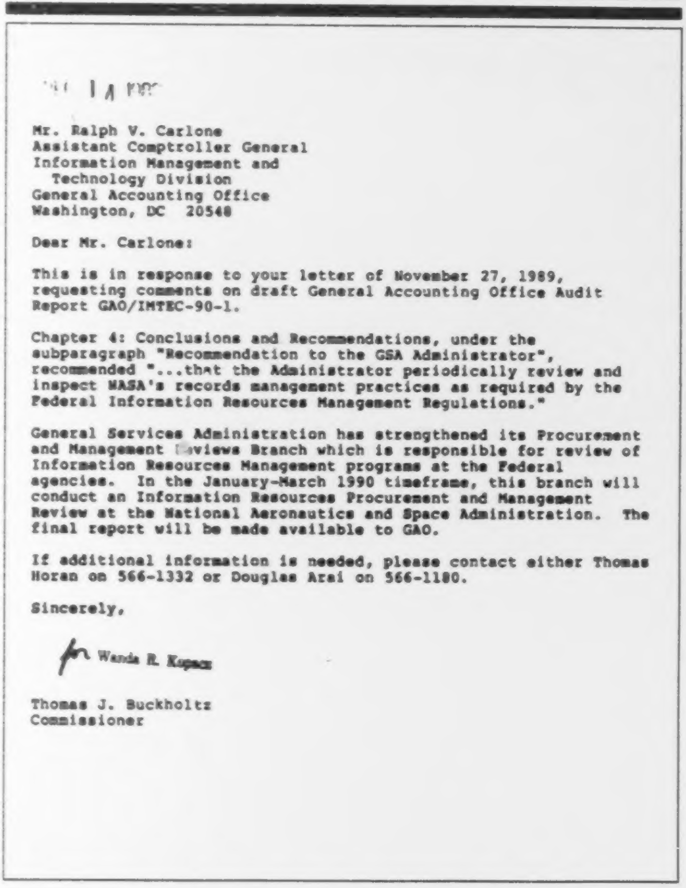
[1] JPL Interoffice Memorandum - Federal Archives Earthquake Damage, July 14, 1986 (emphasis added).

GSA's Comments



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Mr. Ralph V. Carlone
Assistant Comptroller General
Information Management and
  Technology Division
General Accounting Office
Washington, DC 20548

Dear Mr. Carlone:

This is in response to your letter of November 27, 1989, requesting comments on draft General Accounting Office Audit Report GAO/IMTEC-90-1.

Chapter 4: Conclusions and Recommendations, under the subparagraph "Recommendation to the GSA Administrator", recommended "...that the Administrator periodically review and inspect NASA's records management practices as required by the Federal Information Resources Management Regulations."

General Services Administration has strengthened its Procurement and Management Reviews Branch which is responsible for review of Information Resources Management programs at the Federal agencies. In the January-March 1990 timeframe, this branch will conduct an Information Resources Procurement and Management Review at the National Aeronautics and Space Administration. The final report will be made available to GAO.

If additional information is needed, please contact either Thomas Horan on 566-1332 or Douglas Arai on 566-1180.

Sincerely,

for Wanda R. Kopacz

Thomas J. Buckholtz
Commissioner

Appendix VII

Major Contributors to This Report

Information Management and Technology Division, Washington, D.C.	Stephen A. Schwartz, Assistant Director Ronald W. Beers, Assignment Manager Mirko J. Dolak, Evaluator-in-Charge David T. Schwartz, Evaluator Darlene D. Rush, Evaluator
Los Angeles Regional Office	Allan Roberts, Regional Assignment Manager Jeffrey N. Webster, Evaluator Lisa Rodely, Evaluator Dawn M. Sellers, Evaluator

United States General Accounting Office

GAO

Fact Sheet for Congressional Requesters

April 1990

NASA ADP PROCUREMENT

Contracting and Market Share Information

GAO/IMTEC-90-39FS

GAO

United States
General Accounting Office
Washington, D.C. 20548

Information Management and
Technology Division

B-238835

April 20, 1990

The Honorable John Conyers, Jr.
Chairman, Committee on Government Operations
House of Representatives

The Honorable Frank Horton
Ranking Minority Member, Committee
on Government Operations
House of Representatives

This report responds to your February 1989 requests for a comprehensive review of federal agencies' compatible computer procurements.[1] In your initial requests and in subsequent discussions with your offices, we were asked to answer several specific questions about agencies' procurements of mainframe computers and mainframe peripheral equipment. Your questions focused on identifying the extent to which agencies' procurements of mainframe computers and mainframe peripherals required compatibility with International Business Machines (IBM) or any other computer manufacturer. You were also interested in knowing details such as the identification of manufacturers whose equipment was acquired by each agency and the procurement methods used to obtain equipment.

In addition to this report on the National Aeronautics and Space Administration (NASA), we previously reported similar information on the Navy (including the Marine Corps),[2] the Army,[3] and the Air Force.[4] Information on the remaining 30 agencies we included in our work will be reported after we have fully analyzed procurement data we collected from them.

---

[1] A compatible procurement requires hardware or software that functions like specified or existing hardware or software, with little or no modification. Competition in such procurements may occur between manufacturers and marketers—such as system developers and system integrators—to supply equipment that meets the compatible requirements. Since there is the potential for competition between manufacturers and marketers, a compatible procurement does not necessarily result in the award of a sole source contract.

[2] NAVY ADP PROCUREMENT: Contracting and Market Share Information (GAO/IMTEC-89-66FS, Sept. 15, 1989).

[3] ARMY ADP PROCUREMENT: Contracting and Market Share Information (GAO/IMTEC-90-28FS, Mar. 1, 1990).

[4] AIR FORCE ADP PROCUREMENT: Contracting and Market Share Information (GAO/IMTEC-90-35FS, Apr. 9, 1990).

Results in Brief

The information we obtained from NASA shows that during the 3 1/2 fiscal years ending in March 1989, 68 percent of NASA's procurements for mainframes and mainframe peripherals required some type of compatibility. NASA required IBM compatibility in 96 of its 127 compatible procurements (76 percent). Of the 31 remaining compatible procurements, NASA required that 13 have Control Data Corporation compatibility, 11 have Honeywell Bull compatibility, and 7 have Unisys compatibility.[5] When NASA's procurements required IBM compatibility, IBM equipment was supplied in 68 of those 96 IBM-compatible procurements (71 percent). Overall, IBM equipment was supplied for more NASA mainframe and mainframe peripheral equipment procurements than any other manufacturer's equipment, including both compatible and other procurements where no compatibility was required. When we used dollars for comparison—as opposed to the number of procurements—we found that NASA obligated more dollars to (1) IBM-compatible procurements than to any other type of compatible procurement and (2) purchases of IBM equipment than to any other manufacturer's equipment.

As requested in discussions with your offices, we also obtained information from NASA on the procurement methods it uses, including NASA's use of contractors that participate in the Small Business Administration's program for small disadvantaged businesses—known as 8(a) contractors. Further, we received information from NASA on its operating system software procurements. The detailed questions you asked and our answers are summarized in appendix I. Appendix II contains tables with detailed statistics that are the basis for our answers to your questions.

We are reporting information for the 3 1/2 fiscal years from October 1, 1985, through March 31, 1989. All the information is based on NASA's response to a questionnaire we devised and distributed to 35 agencies. We did not independently validate the information, which NASA supplied in August 1989, nor did we evaluate any documentation related to individual NASA procurements. However, we checked NASA's information for consistency with the instructions for our questionnaire and made appropriate revisions. At your request, we did not solicit or obtain comments from NASA on this report. Appendix III contains additional details on the objective, scope, and methodology of our work.

---

[5] Since several companies manufacture and market IBM-compatible equipment, competition in IBM-compatible procurements may occur among a variety of manufacturers and marketers. However, there are few if any companies that manufacture equipment compatible with Control Data Corporation, Honeywell Bull, or Unisys. As a result, competition in procurements requiring Control Data Corporation, Honeywell Bull, or Unisys compatibility generally occurs only between the manufacturer of the required equipment and companies marketing that manufacturer's equipment.

As arranged with your offices, unless you publicly announce its contents earlier, we plan no further distribution of this report until 30 days after the date of this letter. We will then send copies to NASA, and will also make copies available to others upon request.

This information was compiled under the direction of Jack L. Brock, Jr., Director, Government Information and Financial Management, who can be contacted at (202) 275-3195, should you require additional information. Other major contributors to this report are listed in appendix IV.

Ralph V. Carlone

Ralph V. Carlone
Assistant Comptroller General

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Abbreviations

ADP	automated data processing
GAO	General Accounting Office
GSA	General Services Administration
IBM	International Business Machines
IMTEC	Information Management and Technology Division
NASA	National Aeronautics and Space Administration

Appendix I

Questions and Answers About NASA Procurements

What are the numbers and dollar amounts of NASA's mainframe and mainframe peripheral procurements requiring compatibility and is there any trend toward the increased use of compatible procurements?

NASA had a total of 187 procurements and obligated a total of $104.4 million for mainframe computers and mainframe peripherals during the 3 1/2 fiscal years ending in March 1989. According to NASA statistics, compatible procurements comprised 127 of NASA's 187 total procurements and represented $69.4 million of the $104.4 million obligated. In each of the 3 1/2 fiscal years—using NASA's number of procurements as a measure—the percentage of compatible procurements versus other procurements was 56 percent or higher. During the same time period, the percentage of dollars obligated to compatible procurements versus other procurements was 58 percent or higher in each year. There was decreased use of compatible procurements over the 3 1/2 years when the percentage of compatible procurements is measured in number of procurements. However, when NASA's percentage of compatible procurements is measured in dollar obligations, there was increased use of compatible procurements over the 3 1/2 year period.

Figure I.1: Number of NASA Mainframe and Mainframe Peripheral Procurements

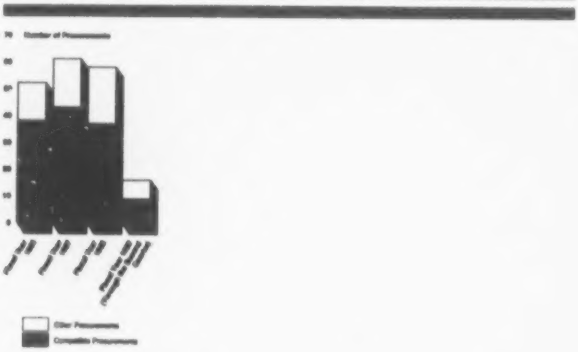
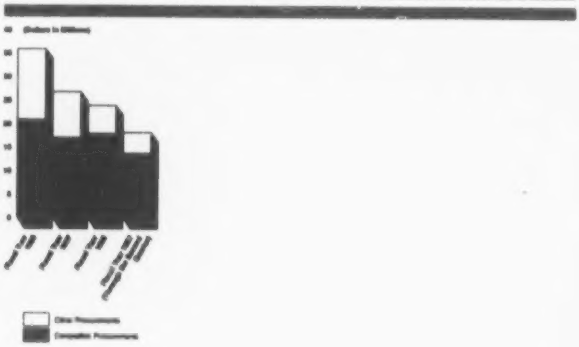


Figure I.2: Dollars for NASA Mainframe and Mainframe Peripheral Procurements



What is the distribution of NASA's compatible mainframe and mainframe peripheral procurements according to type of compatibility?

Those procurements that NASA identified as having a compatible requirement were for either Control Data Corporation, Honeywell Bull, IBM, or Unisys compatibility. Specifically, 96 of the 127 procurements were to satisfy IBM-compatible requirements representing $47.2 million of $69.4 million obligated for all compatible procurements. Also, Control Data Corporation-compatible requirements accounted for 13 procurements and $6.7 million while Honeywell Bull-compatible requirements represented 11 procurements and $9.2 million. Unisys-compatible requirements represented 7 of the 127 procurements and $6.3 million of the $69.4 million in obligations.

Figure I.3: Number of NASA Compatible Procurements According to Type of Compatibility

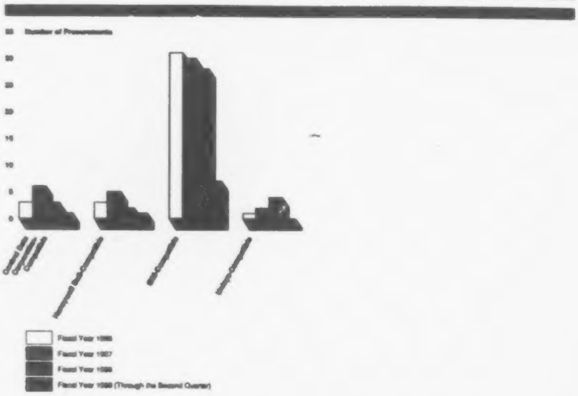
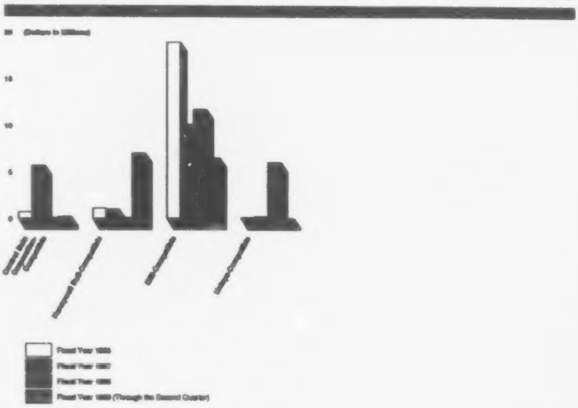


Figure I.4: Dollars for NASA Compatible Procurements According to Type of Compatibility



What equipment manufacturers are involved in NASA's IBM-compatible mainframe and mainframe peripheral procurements?

NASA obtained IBM equipment in the majority of its IBM-compatible procurements in each of fiscal years 1986 through 1988. In the first half of fiscal year 1989, NASA obtained Amdahl equipment in most IBM-compatible procurement situations. Of the 96 IBM-compatible procurements during fiscal years 1986 through 1989 (through the second quarter), 68 (71 percent) resulted in NASA obtaining IBM equipment. Similarly, of the $47.2 million obligated to IBM-compatible procurements, $29.3 million (62 percent) was for procurements involving IBM equipment. In addition to IBM and Amdahl, other manufacturers involved in NASA's IBM-compatible procurements included Memorex, National Advanced Systems, and Storage Technology Corporation.

Figure I.5: Number of NASA IBM-Compatible Procurements According to Manufacturer of Equipment

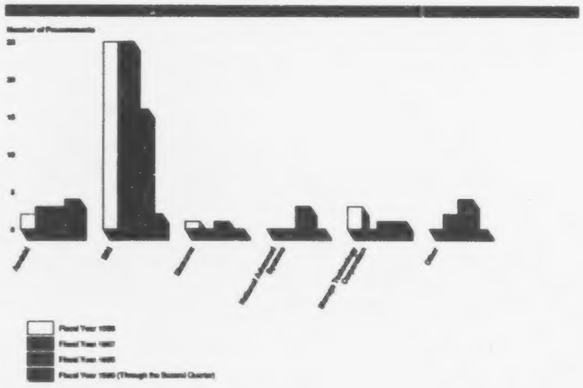
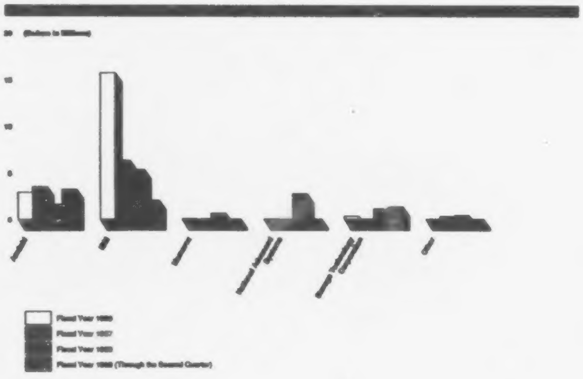


Figure I.6: Dollars for NASA IBM-Compatible Procurements According to Manufacturer of Equipment



What procurement methods were used to obtain all types of compatible mainframe computers and mainframe peripheral equipment? And, did NASA frequently use new contracts with 8(a) contractors to obtain compatible mainframes and mainframe peripherals?

Using the number of procurements as a measure, General Services Administration (GSA) schedule purchases were the most frequently used method of obtaining equipment when NASA identified compatible requirements. However, when measured using obligated dollars, NASA performed most procurements that required compatibility through competitive new contracts with more than one offeror participating in the selection process. New contracts with 8(a) firms were not used by NASA in any of the 127 compatible procurements.

Figure I.7: Number of NASA Compatible Procurements According to Procurement Method

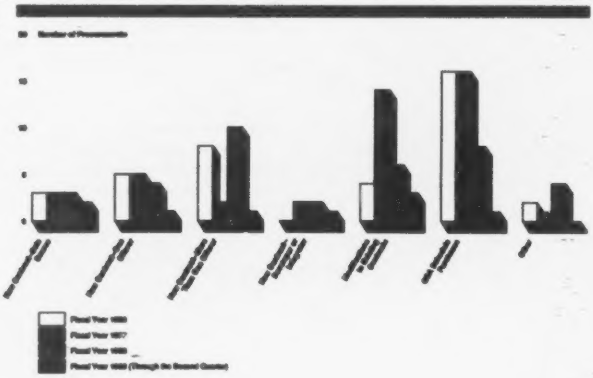
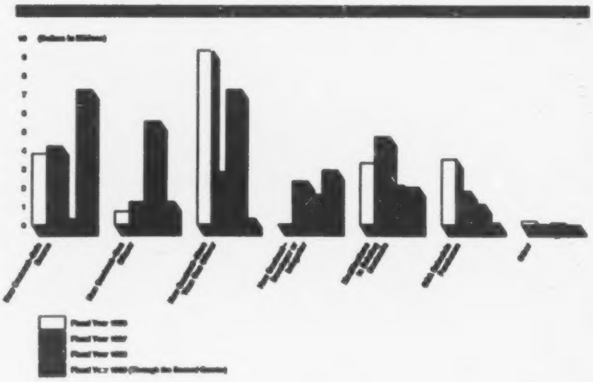


Figure I.8: Dollars for NASA Compatible Procurements According to Procurement Method



What procurement methods were used to obtain IBM-compatible mainframe computers and mainframe peripheral equipment? And, did NASA frequently use new contracts with 8(a) contractors to obtain IBM-compatible mainframes and mainframe peripherals?

NASA most frequently used GSA schedule purchases as the procurement method for obtaining IBM-compatible equipment. However, new contracts with more than one offeror participating in the selection process accounted for more dollar obligations than any other procurement method. New contracts with 8(a) firms were not used by NASA for any of the 96 IBM-compatible procurements during the 3 1/2 year period.

Figure I.9: Number of NASA IBM-Compatible Procurements According to Procurement Method

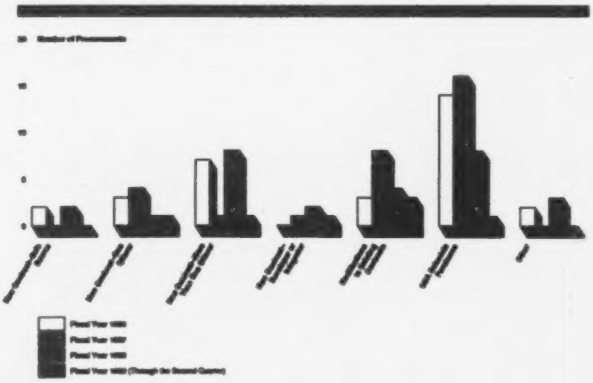
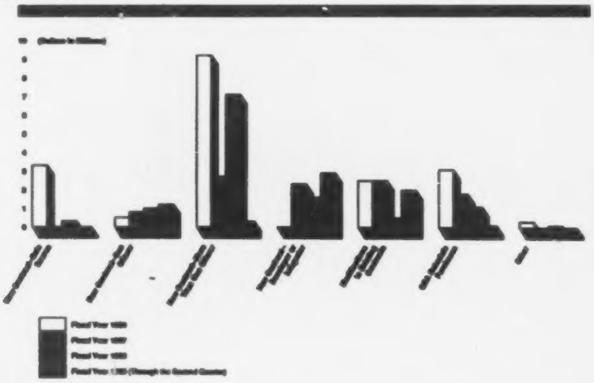


Figure I.10: Dollars for NASA IBM-Compatible Procurements According to Procurement Method



What equipment manufacturers are involved in NASA's mainframe and mainframe peripheral procurements, including both procurements where compatibility is required and procurements with no compatibility requirement?

IBM equipment was most frequently supplied to NASA for mainframe and mainframe peripheral procurements in each of fiscal years 1986 through 1988 and for the first half of fiscal year 1989, with 105 out of 187 total procurements. Additionally, using obligated dollars as the measure, NASA's obligations for IBM equipment during the same 3 1/2 year period were $56 million of a total of $104.4 million. Amdahl, Control Data Corporation, Honeywell Bull, National Advanced Systems, Storage Technology Corporation, and Unisys equipment was also supplied to NASA during the 3 1/2 years.

Figure I.11: Number of NASA Mainframe and Mainframe Peripheral Procurements According to Manufacturer of Equipment

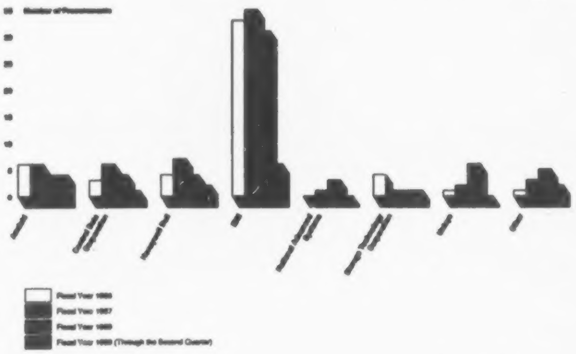
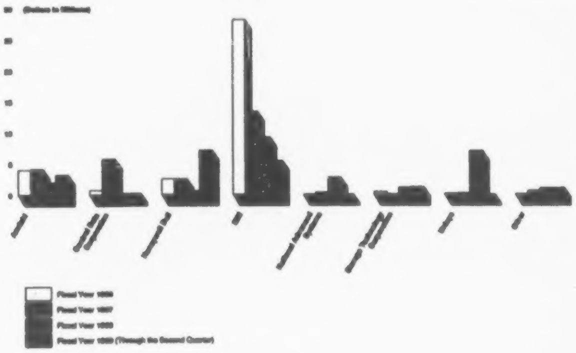


Figure I.12: Dollars for NASA Mainframe and Mainframe Peripheral Procurements According to Manufacturer of Equipment



How much mainframe computer operating system software did NASA procure during the 3 1/2 year period ending March 31, 1989, and what types of mainframe computers was the software for?

NASA had 85 contracts for operating system software totaling $9.1 million in obligations during the 3 1/2 year period. Seventy-eight of these, accounting for $8.3 million in obligations, were for IBM-compatible mainframes, with the remainder divided among Control Data Corporation, Honeywell Bull, and Unisys mainframes.

Appendix II

Detailed Statistics on NASA Procurements

Table II.1: NASA Mainframe and Mainframe Peripheral Procurements

Dollars in millions

	Fiscal Year 1986		Fiscal Year 1987		Fiscal Year 1988		Fiscal Year 1989[a]		Total	
	Number	Amount	Number	Amount	Number	Amount	Number	Amount	Number	Amount
Compatible	38	$20.8	43	$17.0	37	$17.9	9	$13.7	127	$69.4
Other	14	15.0	18	9.7	21	5.9	7	4.4	60	35.0
Total	**52**	**$35.8**	**61**	**$26.7**	**58**	**$23.8**	**16**	**$18.1**	**187**	**$104.4**
Compatible Percent of Total	73%	58%	70%	64%	64%	75%	56%	76%	68%	66%

[a] Fiscal year 1989 through the second quarter.

Table II.2: NASA Compatible Procurements According to Type of Compatibility

Dollars in millions

	Fiscal Year 1986		Fiscal Year 1987		Fiscal Year 1988		Fiscal Year 1989[a]		Total	
	Number	Amount	Number	Amount	Number	Amount	Number	Amount	Number	Amount
Control Data Corporation-Compatible	3	$0.7	6	$5.7	3	$0.1	1	$0.2	13	$6.7
Honeywell Bull-Compatible	3	1.1	5	1.0	2	0.1	1	7.0	11	9.2
IBM-Compatible	31	18.9	30	10.1	28	11.7	7	6.5	96	47.2
Unisys-Compatible	1	0.1	2	0.2	4	6.0	0	0.0	7	6.3
Total	**38**	**$20.8**	**43**	**$17.0**	**37**	**$17.9**	**9**	**$13.7**	**127**	**$69.4**

[a] Fiscal year 1989 through the second quarter.

Table II.3: NASA IBM-Compatible Procurements According to Manufacturer of Equipment

Dollars in millions

	Fiscal Year 1986		Fiscal Year 1987		Fiscal Year 1988		Fiscal Year 1989[a]		Total	
	Number	Amount	Number	Amount	Number	Amount	Number	Amount	Number	Amount
Amdahl	2	$2.9	3	$3.5	3	$1.6	4	$3.2	12	$11.2
IBM	25	15.7	25	6.3	16	5.3	2	2.0	68	29.3
Memorex	1	b	0	0.0	1	0.6	0	0.0	2	0.6
National Advanced Systems	0	0.0	0	0.0	3	2.7	0	0.0	3	2.7
Storage Technology Corporation	3	0.3	0	0.0	1	1.1	1	1.3	5	2.7
Other	0	0.0	2	0.3	4	0.4	0	0.0	6	0.7
Total	**31**	**$18.9**	**30**	**$10.1**	**28**	**$11.7**	**7**	**$6.5**	**96**	**$47.2**

[a] Fiscal year 1989 through the second quarter.

[b] Less than $50,000.

Table II.4: NASA Compatible Procurements According to Procurement Method

Dollars in millions

	Fiscal Year 1986		Fiscal Year 1987		Fiscal Year 1988		Fiscal Year 1989[a]		Total	
	Number	Amount	Number	Amount	Number	Amount	Number	Amount	Number	Amount
New Contract—Sole Source	3	$3.8	3	$4.2	3	$0.3	2	$7.2	11	$15.5
New Contract—One Offeror	5	0.7	5	1.2	4	5.5	1	1.2	15	8.6
New Contract—More Than One Offeror	8	9.3	2	2.8	10	7.2	1	0.3	21	19.6
New Contract—Developer or Integrator	0	0.0	2	2.3	2	1.6	1	2.9	5	6.8
Modifications to Existing Contracts	4	3.3	14	4.7	6	2.1	3	2.0	27	12.1
GSA Schedule Purchases	16	3.5	16	1.8	8	1.1	1	0.1	41	6.5
Other	2	0.2	1	b	4	0.1	0	0.0	7	0.3
Total	**38**	**$20.8**	**43**	**17.0**	**37**	**$17.9**	**9**	**$13.7**	**127**	**$69.4**

[a] Fiscal year 1989 through the second quarter.

[b] Less than $50,000

Table II.5: NASA IBM-Compatible Procurements According to Procurement Method

Dollars in millions

	Fiscal Year 1986		Fiscal Year 1987		Fiscal Year 1988		Fiscal Year 1989[a]		Total	
	Number	Amount	Number	Amount	Number	Amount	Number	Amount	Number	Amount
New Contract—Sole Source	2	$3.3	0	$0.0	2	$0.3	0	$0.0	4	$3.6
New Contract—One Offeror	3	0.5	4	0.8	1	1.0	1	1.2	9	3.5
New Contract—More Than One Offeror	7	9.2	1	2.7	8	7.1	1	0.3	17	19.3
New Contract—Developer or Integrator	0	0.0	1	2.3	2	1.6	1	2.9	4	6.8
Modifications to Existing Contracts	3	2.5	8	2.5	4	0.5	3	2.0	18	7.5
GSA Schedule Purchases	14	3.1	16	1.8	8	1.1	1	0.1	39	6.1
Other	2	0.3	0	0.0	3	0.1	0	0.0	5	0.4
Total	**31**	**$18.9**	**30**	**$10.1**	**28**	**$11.7**	**7**	**$6.5**	**96**	**$47.2**

[a] Fiscal year 1989 through the second quarter.

Table II.6: NASA Mainframe and Mainframe Peripheral Procurements According to Manufacturer of Equipment

Dollars in millions

	Fiscal Year 1986		Fiscal Year 1987		Fiscal Year 1988		Fiscal Year 1989[a]		Total	
	Number	Amount	Number	Amount	Number	Amount	Number	Amount	Number	Amount
Amdahl	6	$4.0	6	$4.1	4	$2.0	4	$3.2	20	$13.3
Control Data Corporation	3	0.7	6	5.7	4	0.2	1	0.2	14	6.8
Honeywell Bull	4	2.5	7	2.5	4	0.6	2	7.1	17	12.7
IBM	33	28.1	35	13.3	31	9.2	6	5.4	105	56.0
Memorex[c]	1	b	0	0.0	1	0.6	0	0.0	2	0.6
National Advanced Systems	0	0.0	1	0.3	3	2.7	0	0.0	4	3.0
Storage Technology Corporation	4	0.4	1	b	1	1.1	1	1.2	7	2.7
Unisys	1	0.1	2	0.2	6	7.0	0	0.0	9	7.3
Other	0	0.0	3	0.6	4	0.4	2	1.0	9	2.0
Total	**52**	**$35.8**	**61**	**$26.7**	**58**	**$23.8**	**16**	**$18.1**	**187**	**$104.4**

[a] Fiscal year 1989 through the second quarter.

[b] Less than $50,000.

[c] Included in Other on Figure I.11 and Figure I.12.

Table II.7: NASA Operating System Software Contracts According to Type of Mainframe

Dollars in millions

	Fiscal Year 1986		Fiscal Year 1987		Fiscal Year 1988		Fiscal Year 1989[a]		Total	
	Number	Amount	Number	Amount	Number	Amount	Number	Amount	Number	Amount
Control Data Corporation	0	$0.0	0	$0.0	2	$0.1	0	$0.0	2	$0.1
Honeywell Bull	1	b	1	0.2	0	0.0	1	0.2	3	0.4
IBM-Compatible	16	1.5	21	3.1	27	2.3	14	1.4	78	8.3
Unisys	0	0.0	1	0.1	1	0.2	0	0.0	2	0.3
Total	**17**	**$1.5**	**23**	**$3.4**	**30**	**$2.6**	**15**	**$1.6**	**85**	**$9.1**

[a] Fiscal year 1989 through the second quarter.

[b] Less than $50,000.

Objective, Scope, and Methodology

In February 1989 we were requested by the Chairman and the Ranking Minority Member, House Committee on Government Operations, to perform a comprehensive review of the government's use of IBM-compatible automated data processing (ADP) procurements. In response to the requests and in discussions with the Chairman's and Ranking Minority Member's offices, we agreed that procurements of mainframes and mainframe peripherals would be included in our review, with emphasis on compatible procurements. Our review covered procurements during the 3 1/2 fiscal years ending in March 1989, at 35 federal agencies.

Our primary objective was to obtain and analyze information on specific aspects of each agency's ADP-related procurements. This report focuses on NASA and includes the number and aggregate dollar value of NASA's mainframe-related contracts, distribution of procurements among equipment manufacturers, and breakdown of various procurement methods NASA used to obtain mainframe-related equipment. Further, as requested, we obtained data on NASA's procurements of mainframe computer operating system software.

We used the following mutually exclusive procurement methods to group NASA's procurements. The first three methods represent specific types of new contracts with mainframe and peripheral equipment manufacturers. These consist of sole source new contracts, new contracts that resulted from competitive procedures where only one offeror remained in the procurement at the time the awardee was selected, and new contracts that resulted from competitive procedures where the awardee was selected from among multiple competitors. We also included a category for new contracts with system developers and integrators—except any contracts separately categorized as awarded to 8(a) firms. We also obtained and analyzed data on NASA's modifications to existing contracts, the use of GSA's multiple award schedule contracts, and other miscellaneous procurement methods.

To accomplish our objective and facilitate NASA's information gathering, we designed a questionnaire which, when properly completed by NASA, provided us with the necessary information. Our questionnaire included several charts and provided detailed instructions, with definitions and examples, to help NASA identify and report the relevant information. Our questionnaire instructions cited pertinent federal regulations to ensure consistency in understanding of the terms used and to identify key definitions.

In preparing instructions for our questionnaire, we recognized the need to clearly and consistently identify mainframe computers, as opposed to superminicomputers and supercomputers. Because technology changes, criteria such as storage capacity, processing speed, physical size, cooling requirements, and cost do not provide an adequate basis for clear and consistent identification of mainframes. Therefore, after consulting with computer vendors, GSA, other federal agency officials, and Datapro,[6] we considered vendor marketing strategy—in addition to computer architecture and performance—as the basis for classifying particular computers as superminicomputers, mainframes, or supercomputers. Like Datapro, we classified as mainframes some smaller and less expensive models if they belong to a product line, or family, of mainframes sharing a common architecture or operating system. However, models with similar performance characteristics that do not belong to a mainframe family and are manufactured by companies that are not traditionally recognized as mainframe manufacturers were not classified as mainframes. We provided a list of mainframe manufacturers and models in the instructions for our questionnaire as examples of computers that agencies should include in completing the questionnaire.

We obtained comments on preliminary copies of our questionnaire from information resources management officials at the Departments of Agriculture and Transportation, to aid in ensuring the questionnaire's clarity. After modifying the questionnaire based on comments received from officials at the Departments of Agriculture and Transportation, we asked the senior information resources management officials at NASA and 34 other federal agencies to complete the questionnaire.

Our questionnaire was furnished to NASA in mid-April 1989. In May 1989 we discussed our questionnaire with NASA officials and indicated that their response should include all mainframes and peripherals classified as general purpose equipment. Upon receiving NASA's response in August 1989, the information was reviewed to determine if the instructions were followed correctly and if the information was clear and consistent. Although we did not independently validate the information supplied in the NASA response, our questionnaire contained several internal checks to determine if inconsistencies were present. In some situations we modified the data on the basis of discussions with NASA officials. In other cases we excluded inappropriate data. For example, we directed the agencies to include only procurement data for mainframe-related equipment. However, in a few instances NASA included procurements for computers other than mainframes. In order to maintain consistency in the statistics across the 35 federal agencies, any procurements reported by NASA for equipment other than mainframes and related peripherals were deleted from our analysis. Our work did not include solicitation or evaluation of documents related to NASA's individual procurements. The figures and tables in appendixes I and II were developed from our analysis.

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[6] Datapro is a trade publication that provides detailed information on computers, peripheral equipment, and software.

We did not solicit or obtain comments from NASA about this report, however, we discussed our scope and methodology with NASA officials in February 1990. Our review was conducted from February 1989 through February 1990. We discussed our work with NASA officials at NASA headquarters. Additionally, meetings were conducted with the Department of Agriculture, the Department of Transportation, and the General Services Administration in Washington, D.C. Our work was performed in accordance with generally accepted government auditing standards.

Appendix IV

Major Contributors to This Report

Information Management and Technology Division, Washington, D.C.

Mark E. Heatwole, Assistant Director
Mark T. Bird, Evaluator-in-Charge
Darlene D. Rush, Evaluator
Charles S. Stanley, Evaluator
Peter C. Wade, Evaluator

United States General Accounting Office

GAO

Report to the Chairman, Committee on Science, Space, and Technology, House of Representatives

May 1990

SPACE COMMUNICATIONS

Performance of NASA's White Sands Ground Terminal

GAO/IMTEC-90-56

GAO

United States
General Accounting Office
Washington, D.C. 20548

Information Management and
Technology Division

B-239284

May 29, 1990

The Honorable Robert A. Roe
Chairman, Committee on Science,
Space, and Technology
House of Representatives

Dear Mr. Chairman:

This report responds to your request for information about the performance and reliability of the National Aeronautics and Space Administration's (NASA) White Sands ground terminal in White Sands, New Mexico. The White Sands terminal is the main ground component of NASA's Tracking and Data Relay Satellite System (TDRSS), which also includes three space-based satellites and the network control center at the Goddard Space Flight Center in Greenbelt, Maryland.

Various satellites and the space shuttle use TDRSS to relay tracking and scientific data to users. This relay through the White Sands terminal is essential to the safety of NASA astronauts and the receipt of scientific data from space experiments. In our April 1989 report[1] to you on NASA's communications support for earth orbiting spacecraft, we noted problems with the reliability of the automated equipment and software at the White Sands terminal. As agreed by your office, our current objective was to determine how NASA evaluates and assesses the performance and reliability of this terminal. Details on our objective, scope, and methodology are in appendix I.

Results in Brief

NASA does not evaluate the reliability of the White Sands terminal. Instead, it assesses performance in terms of how the terminal met the user's data transmission needs, which it calls user support proficiency. Given this criterion, NASA has exceeded its goal of 95 percent user support proficiency since 1986 and is, on average, delivering telecommunications services to users about 99 percent of the time when scheduled to do so. Moreover, TDRSS users expressed general satisfaction about the services they received.

NASA's user support proficiency measure does not address the terminal's reliability or availability, which are standard engineering measures of equipment failure rates and repair times, and of the total time the equipment is available for use so that predictions can be made about future performance. NASA cannot use these measures because the terminal lacks the necessary diagnostic capability to capture information on the incidence and duration of equipment failures.

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[1] *Space Operations: NASA's Communications Support for Earth Orbiting Spacecraft* (GAO/IMTEC-89-41, Apr. 7, 1989).

Use of the White Sands terminal is expected to increase significantly during the next several years. In June 1989, demand for high data rate telecommunications services—one of several types provided to users—was about 13 percent of available TDRSS capacity. However, demand is projected to increase to about 42 percent in 1993. Without reliability and availability data, NASA officials cannot predict how well the terminal will perform or how long it will be available for use in the future.

NASA plans to replace the White Sands terminal in 1993. Recognizing that increased demand for services in the 1990s will require greater assurance that the new terminal be reliable and available, NASA's design and development contract for the new terminal requires a diagnostic capability as well as specifications for the standard measurements of reliability and availability to determine system performance. NASA also plans to upgrade the old terminal after the new one becomes operational. The estimated cost of these projects is $427 million.

Background

In 1983, NASA launched and began operating its first TDRSS satellite. TDRSS became fully operational in June 1989 with its set of two active satellites and one spare. The active satellites are located over the Atlantic Ocean, off the coast of Brazil; and over the Pacific Ocean, southwest of the Hawaiian Islands. The spare is located between the two and can be used if a major problem occurs with one of the active satellites. TDRSS allows an earth orbiting spacecraft, like the space shuttle, to relay its communications through the active TDRSS satellites to the White Sands terminal and on to its users.

The types of communications relayed through TDRSS include (1) data from spacecraft on their orbital positions, (2) scientific information collected by on-board instruments, (3) commands from users to operate the spacecraft, and (4) engineering data on the health and safety of user spacecraft. Communications through TDRSS are available 24 hours a day, 7 days a week.

TDRSS Usage Is Increasing

Although TDRSS capacity exceeds present use, NASA anticipates demand for services will significantly increase in the 1990s. Since TDRSS began initial operations in 1983, NASA has provided services to various spacecraft including the space shuttle, the Solar Mesosphere Explorer, the Earth Radiation Budget Satellite, Solar Maximum Mission, and LANDSAT 4 and 5. In addition, a new generation of spacecraft are now using TDRSS, including the Hubble Space Telescope and the Cosmic Background Explorer. NASA statistics indicate that since 1983, actual use of TDRSS' high data rate telecommunications services reached a high of about 13 percent of capacity in mid-1989 and is projected to increase to about 42 percent of capacity in 1993.

According to NASA officials, the maximum operating capacity for high data rate services is estimated at 70 to 75 percent of total time available. Operating continuously above this level would result in a rapid decline in service. Under normal circumstances, about 25 to 30 percent is required for handling peak work loads, as well as for factors such as establishing communications visibility—the time needed to line up a user satellite with a TDRSS satellite so communications can be relayed to the ground terminal.

Terminal Problems Are Being Addressed

The White Sands terminal is contractor owned and operated at a cost of about $25 million annually, according to a NASA budget manager. The terminal has two principal functions: (1) to safely operate and maintain the three TDRSS relay satellites, and (2) to provide uninterrupted communication between earth orbiting spacecraft and their users. The terminal was designed to support spacecraft users from 1983 through 1993. Between 1983 and 1985, NASA recognized various problems with TDRSS, including the terminal, and began a comprehensive study to identify problems needing resolution.

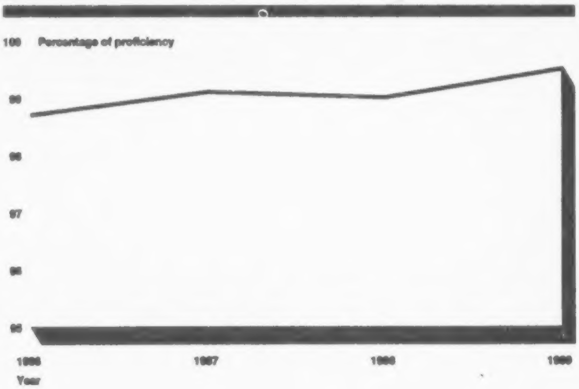
Having identified problems in system design, tracking, operations, and testing, NASA sponsored a 5-year terminal enhancement project, costing about $34 million, scheduled to be completed in July 1990. The project seeks to improve the reliability, maintainability, and availability of the terminal through the end of its operational life in 1993. For example, NASA upgraded, added, and replaced various equipment components of its testing, automated data processing, radio frequency, command, and monitoring systems to reduce failure rates and to improve reliability and availability.

NASA plans to replace the White Sands terminal in 1993. NASA then plans to completely upgrade the old terminal, making it identical to the new one, in order to provide additional capacity and backup capability to support TDRSS demand in the 1990s. Given an overall investment of about $427 million for building the new terminal and upgrading the old one, NASA plans no major interim upgrades of the old terminal. However, NASA officials said they would continue to make minor enhancements until shortly before the new one becomes operational.

Terminal Is Generally Meeting User Needs

Statistics from 1986 to 1989, confirmed by discussions with TDRSS users, indicate the terminal exceeds NASA's performance expectations. NASA officials told us their primary indicator of overall terminal performance was user support proficiency—a measure which compares the actual amount of communications relay time provided to users with the amount of time scheduled for them. As shown in the figure below, NASA's annual support proficiency statistics from 1986 to 1989 show that the terminal exceeded NASA's goal of 95 percent user support proficiency and was, on average, providing communications services to users about 99 percent of the time when scheduled to do so.

Figure 1: User Support Proficiency



User satisfaction is another indicator of terminal performance. Users submit their original requests for telecommunications services to the network control center at Goddard at least 3 weeks before the services are needed. The control center aggregates these requests and during the ensuing 3 weeks negotiates a final telecommunications schedule with all spacecraft users based on priority ranking, planned hardware and software upgrades, and maintenance schedules. Although the control center sets and maintains user schedules, the contractor who operates the terminal is responsible for keeping the equipment functioning to support the user schedules.

Users we interviewed were generally satisfied with the telecommunications services they had received. For example, a representative from the shuttle program, a high priority user, said he was satisfied with the services provided, and added that shuttle data transmissions can only be preempted by an emergency on board another spacecraft. Should this occur, scientific experiments can generally still be performed because the data from these experiments are recorded on tape. Should transmissions be interrupted, spacecraft tape recorders can be rewound and the data retransmitted at a later time. The shuttle representative was confident that the terminal will be able to provide adequate service to meet the shuttle's needs until 1993, when the terminal is scheduled to be replaced.

LANDSAT users were also generally satisfied with the services received. LANDSAT sells earth images to the private sector, with about 20 percent of the images ordered in advance. LANDSAT users pointed out, however, that LANDSAT spacecraft lacked on-board tape recorders. As such, interruptions in telecommunications resulted in lost images. For example, during the first 5 months of 1989, LANDSAT spacecraft lost 502 minutes of data, representing about 20 percent of the total TDRSS data losses for the period. LANDSAT representatives told us they could not readily determine the financial impact of this loss.

Some users had concerns about the administrative process of using TDRSS. Several mentioned having to negotiate changes in their initial schedule request with NASA due to conflicts with other users or other NASA activities. Despite the additional work and frustrations, users said they generally received adequate transmission time to accomplish their mission objectives. Even when NASA changed a schedule just before transmission time, or when transmissions were interrupted, they said mission impact was usually minimal.

Two users wondered whether TDRSS could meet higher future demand for services. Similar concerns were expressed in a December 1989 NASA report[2] that said

> the practical problems of scheduling and conducting an operation with TDRSS are substantial, even considering the recent redesigns within the network control center. In other words, the current design and implementation for scheduling and operationally utilizing TDRSS is fragile. There is considerable uneasiness that the TDRSS, when confronted by increasing high priority loading, is likely to become grossly inefficient and that low priority users will therefore be left without support.

System Reliability and Availability Are Uncertain

Besides user support proficiency and satisfaction, determining a system's reliability and availability are important. These measures are standard engineering concepts for assessing a terminal's current performance and predicting its future performance. However, NASA and contractor officials at White Sands do not measure system reliability, nor do they maintain sufficient data to determine the total time the system equipment was unavailable for use. As a result, NASA cannot predict how reliably the terminal will perform in the future.

System Reliability

Reliability, a standard engineering indicator of a system's technical performance, measures the actual mean time between component failures and, when compiled over a number of years, can be used to predict the likelihood of system failures under future operating conditions. Thus, data on the failure rates of the terminal equipment could be used to model and predict how reliably it will perform in the 1990s when usage is expected to grow significantly.

But according to NASA's ground terminal manager, the 1976 contract for the design and development of TDRSS did not require the contractor to develop built-in diagnostic capability to monitor the technical reliability of the terminal's equipment. Although such diagnostic capability was available at the time of contract award, NASA wanted to buy telecommunications services, not equipment. Hence, NASA's contract and performance criteria focused on the ultimate delivery of telecommunications services to users, not on equipment reliability. NASA saw the operation, maintenance, performance, and reliability of the equipment as the responsibility of its owner, the contractor.

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[2] Information System Scenarios for Space Science and Applications, Section 2.4.2: Data Relay Satellites and Ground Stations, System Diversity and Dependability, December 1989.

Contractor officials said they cannot measure the mean time between equipment failures, or system reliability, because the terminal's electronic system lacks the comprehensive diagnostic capability necessary to precisely capture real-time data on all equipment failures. As a result, in some cases maintenance personnel become aware of an equipment failure only if it is being used to transmit data at the time of failure. In other words, a component failure in a spare chain of equipment or any unused equipment could go unnoticed until put to use.

In 1988 NASA awarded a contract for the design and development of a new terminal at White Sands by 1993. The terminal manager told us that in contrast to the old one, NASA will own the new terminal and therefore, has developed specifications emphasizing its reliability, availability, and maintainability. These specifications address reliability requirements and call for (1) developing a fault isolation system to identify equipment subcomponent failures, and (2) measuring mean time between failures to determine the terminal's reliability.

System Availability

System availability, another performance indicator focusing on equipment, measures the mean time between component failure and mean time to repair. Availability is computed by dividing the time the system was actually available for use by time it should have been available had it functioned according to specifications.

Although NASA officials said they routinely gathered information on the availability of some terminal equipment, they could not supply detailed data on when it was unavailable. The contractor staff said that they were enhancing the maintenance program during the remaining contract period by developing a management information system to supply this data. Because NASA could not provide comprehensive data on equipment availability or summary information on total system downtime, we could not assess the terminal's overall availability.

As in the case of reliability, NASA's contract specifications for the new terminal require that (1) the system be available 99.9 percent of the time, and (2) actual availability be measured against this performance criteria.

Conclusion

The current performance of the White Sands terminal—using NASA's measurement of support proficiency—is high. However, because the terminal is only processing a small percentage of the estimated future work load, it is not being stressed. In the absence of comprehensive reliability and availability data which is important for assessing system performance under increasing work loads, NASA officials cannot accurately predict how well or how long the terminal will perform in the future.

Responsible officials from NASA provided comments on this report. These comments are included where appropriate. As arranged with your office, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the date of this letter. We will then provide copies to appropriate congressional committees, the Administrator of NASA, and other interested parties upon request.

This work was performed under the direction of Samuel W. Bowlin, Director for Defense and Security Information Systems, who can be reached at (202) 275-4649. Other major contributors are listed in appendix II.

Sincerely yours,

Ralph V. Carlone

Ralph V. Carlone
Assistant Comptroller General

Objective, Scope, and Methodology

In June 1989, the House Committee on Science, Space, and Technology asked for information on how NASA evaluates and assesses the performance and reliability of its White Sands ground terminal. To evaluate the terminal's performance, we reviewed three indicators of a system's performance: NASA's user support proficiency, which measures how well the terminal is meeting user schedules for telecommunications services; user satisfaction; and equipment reliability and availability. We obtained monthly statistics on user support proficiency from NASA and CONTEL, Inc., the contractor. We then compared these performance data to the 95-percent support proficiency requirement established in NASA's performance evaluation plan with CONTEL. We also interviewed NASA officials at the Goddard Space Flight Center in Greenbelt, Maryland, and the White Sands Ground Terminal in White Sands, New Mexico, to determine how they collect, analyze, and report data on user support proficiency. We did not independently test the accuracy of this data.

We also interviewed the principal users of TDRSS on their degree of satisfaction with the terminal's performance. These included project staff from the program offices of Space Shuttle, Solar Mesosphere Explorer, Earth Radiation Budget Satellite, Solar Maximum Mission, and LANDSAT 4 and 5.

We also determined the extent to which NASA and CONTEL use standard engineering measurements of equipment reliability and availability to evaluate the performance of the ground terminal system. We reviewed contract documents to verify whether NASA had required the contractor to perform such measurements and if NASA had also established reliability and availability performance criteria. We also interviewed NASA and contractor officials at the terminal to find out if the system was designed with the diagnostic capability necessary to precisely capture reliability and availability data and, if so, what data were collected.

We obtained comments on this report from officials at NASA headquarters, the Goddard Space Flight Center, and White Sands terminal. Their comments have been incorporated into the report where appropriate. We performed our work from June 1989 to March 1990 in accordance with generally accepted government auditing standards.

Appendix II

Major Contributors to This Report

Information Management and Technology Division, Washington, D.C.	Stephen A. Schwartz, Assistant Director Ronald W. Beers, Assistant Director Leonard J. Latham, Technical Adviser Janice D. Troupe, Evaluator
Denver Regional Office	Ronald J. Guthrie, Regional Management Representative Anthony R. Padilla, Evaluator-in-Charge Elizabeth Donnelly, Evaluator

United States General Accounting Office

GAO

Report to the Chairman, Committee on Science, Space, and Technology, House of Representatives

July 1990

SPACE TRANSPORTATION

NASA Has No Firm Need for Increasingly Costly Orbital Maneuvering Vehicle

GAO
United States
General Accounting Office
Washington, D.C. 20548

National Security and
International Affairs Division

B-239570

July 31, 1990

The Honorable Robert A. Roe
Chairman, Committee on Science,
Space, and Technology
House of Representatives

Dear Mr. Chairman:

As you requested, we have reviewed the National Aeronautics and Space Administration's (NASA) Orbital Maneuvering Vehicle (OMV) program. Specifically, we evaluated the need to continue the OMV program in light of reductions in its capabilities and the reasons for changes in OMV program costs and schedules.

We are sending copies of this report to the Administrator of NASA and appropriate congressional committees. Copies will be made available to other interested parties upon request.

This report was prepared under the direction of Mr. Mark E. Gebicke, Director, NASA Issues, who may be reached on (202) 275-5140 if you or your staff have any questions concerning the report. Major contributors to the report are listed in appendix I.

Sincerely yours,

Frank C. Conahan
Assistant Comptroller General

Executive Summary

Purpose

The Orbital Maneuvering Vehicle (OMV) was conceived in 1986 as a $405 million multipurpose space tug. However, the estimated cost of the program has grown to $736.5 million. In late 1989, the National Aeronautics and Space Administration (NASA) reduced or eliminated some of the OMV's planned capabilities to contain growing program costs.

The Chairman, House Committee on Science, Space, and Technology, asked GAO to determine (1) whether NASA had established a firm need for the OMV and (2) why the program costs have grown so much.

Background

The OMV program was initiated as a way of extending the practical reach of the space shuttle. It was to transport satellites from the shuttle to other orbits, reboost them when their orbits decayed, retrieve and return them to the shuttle when they malfunctioned, and control their reentry into the atmosphere when their useful lives expired. Subsequent OMV enhancements would enable it to refuel satellites in orbit, perform in-orbit satellite repairs, and rescue out-of-control satellites. The OMV was to operate initially from the shuttle's cargo bay but would ultimately operate from the Space Station Freedom.

OMV was designed to be a free-flying, remotely controlled propulsion stage about 15 feet in diameter and 6 feet thick that would be carried into orbit inside the shuttle's cargo bay. Once separated from the shuttle, the OMV would be remotely controlled by astronauts working at consoles on earth.

The OMV's detailed design and development phase began in fiscal year 1986. The cost-plus-award-fee contract provides for the design, development, test, verification, and delivery of one OMV flight vehicle and associated support equipment.

Results in Brief

A firm requirement for the OMV does not exist. NASA can accomplish the OMV's scheduled missions of reboosting the Hubble Space Telescope and deploying and reboosting the Advanced X-ray Astrophysics Facility in other ways that cost less. Other potential missions may or may not materialize, but the OMV would have to be significantly enhanced before NASA could use it on most of these other missions.

Since the OMV's design and development phase began in 1986, estimated OMV program costs have increased by 82 percent, even though the vehicle's capabilities have significantly decreased. The increase is attributable to (1) schedule stretchouts caused by internal NASA budget reductions, (2) program changes, and (3) contract cost growth. Further cost increases appear likely, especially if NASA is to make maximum use of the OMV.

Principal Findings

OMV Is Not Needed for Scheduled Missions

In late 1989, NASA reduced or eliminated a number of planned OMV performance capabilities. The OMV is now being designed principally to reboost the Hubble Space Telescope and deploy and reboost the Advanced X-ray Astrophysics Facility. Several NASA studies show, however, that the shuttle can perform these missions without the OMV.

A recent performance assessment shows that the OMV will not be needed to deploy the Advanced X-ray Astrophysics Facility if advanced solid rocket motors are available on the shuttle. According to the assessment, the shuttle with these motors will be able to deliver this observatory to its desired orbital altitude without the OMV. The first shuttle flight using the advanced motors is scheduled for late 1995—well before the observatory's April 1997 deployment schedule.

Other NASA studies show that the shuttle can maintain the Hubble and the X-ray observatories at acceptable altitudes by reboosting them during regularly scheduled maintenance flights. One or two additional shuttle flights dedicated to reboosting the observatories could be required early in the next century if the OMV is not developed.

The cost of the two additional shuttle flights to reboost the observatories would be about $277 million. The cost of continued development and operation of the OMV for the two missions would be about $716 million—more than two and one-half times the cost of the shuttle flights.

Future Mission for the OMV Uncertain

Program officials have identified other, longer-term missions that they believe the OMV could enhance. For example, an OMV-type vehicle may be needed to help maneuver materials in space if NASA undertakes staffed missions to the moon or to Mars. However, these missions have not yet been approved, and NASA has not decided what equipment would be needed to perform them. If these missions are approved and the OMV is used, capabilities that were removed from the design in 1989 would have to be restored. These capabilities include the addition of advanced solar arrays to allow for basing at Space Station Freedom.

Estimated Costs Continue to Increase

Since the design and development phase began in fiscal year 1986, estimated OMV program costs have incurred a net increase of $331.5 million—from $405.0 million to $736.5 million. Schedule stretchouts caused $256.1 million of the increase. Program changes such as shifting responsibility for OMV operations from Marshall Space Flight Center to the Johnson Space Center added another $105.9 million. The remaining $123.1 million of the increase was attributed to contract cost growth. NASA reduced the program estimate by $153.6 million by eliminating some of the OMV's capabilities and reducing cost reserves. NASA requested $85.4 million in its fiscal year 1991 budget.

The same factors that caused earlier cost increases could cause future increases. According to the Associate Administrator for Space Flight, the OMV program is not immune to future budget cuts, which could cause additional schedule delays and cost increases. Also, program changes are to be expected as a result of the critical design review scheduled for April 1991 and subsequent hardware fabrication and testing. NASA is also concerned about additional contract cost growth. A number of the subcontracts have not yet been awarded, and firm prices have not been negotiated for other subcontracts. The current estimate includes a cost reserve to cover future changes, but the reserve is about half the amount NASA normally includes in cost estimates of programs at this stage of development.

OMV acquisition costs could increase to a cumulative total of $1.3 billion if NASA decided to use the vehicle for other missions, which would involve (1) restoring capabilities eliminated in the 1989 restructuring, (2) purchasing a second vehicle, (3) making the two OMVs compatible with expendable launch vehicles, and (4) purchasing an initial contingent of spare parts. However, NASA considered it unlikely that it would do all of these things.

Recommendation and Agency Action

Continued development of the OMV is not the most cost-effective approach to accomplishing currently scheduled missions and future mission requirements are uncertain. In its draft report GAO therefore recommended that the NASA Administrator terminate the OMV program. NASA terminated the OMV program 6 days after receiving GAO's draft report, citing budget pressures and the absence of a firm, near-term requirement for the vehicle.

Matter for Congressional Consideration

The Congress should deny the $85.4 million requested for OMV development in fiscal year 1991, less any amount needed for termination expenses. According to a preliminary NASA estimate, about $33.2 million of fiscal year 1991 funding will be needed for termination.

Agency Comments

GAO incorporated NASA's comments into this report where appropriate.

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Abbreviations

AXAF	Advanced X-ray Astrophysics Facility
GAO	General Accounting Office
HST	Hubble Space Telescope
NASA	National Aeronautics and Space Administration
OMV	Orbital Maneuvering Vehicle

Chapter 1

Introduction

The National Aeronautics and Space Administration (NASA) is developing the Orbital Maneuvering Vehicle (OMV) to supplement the space shuttle's capability to deliver, retrieve, and service satellites. The OMV is to provide the capability to transport satellites to and from the shuttle's cargo bay and other orbital altitudes and inclinations[1] and to reboost the satellites when their altitudes decay. Other capabilities are to include viewing satellites to help diagnose their condition and controlling the reentry of satellites into the earth's atmosphere when their useful lives expire.

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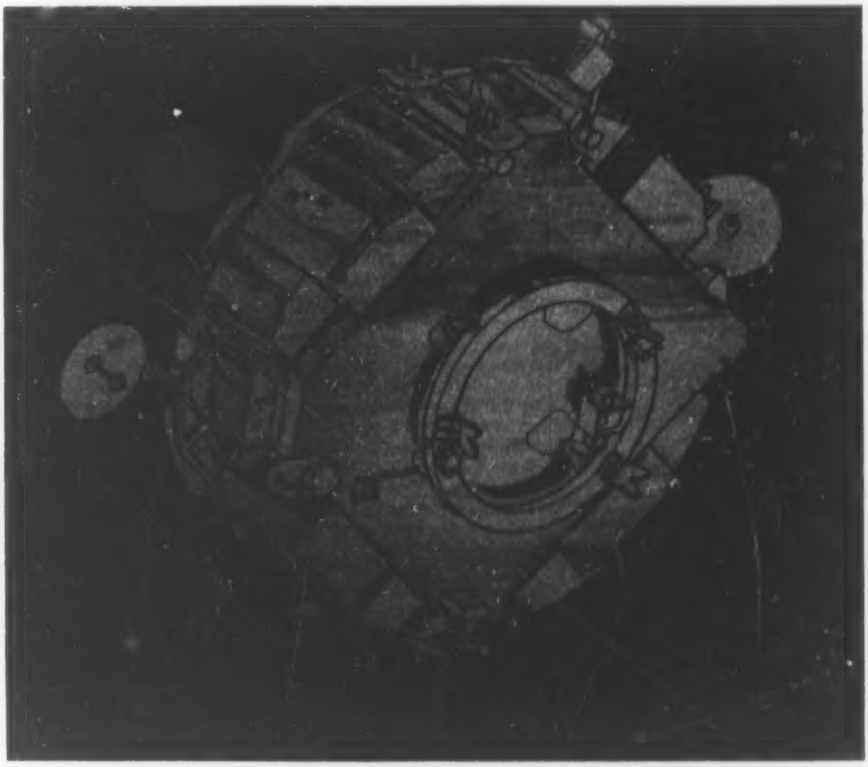
[1] Orbital altitude is a satellite's height above the earth. Inclination is the angle of the satellite's orbit relative to the earth's equator.

Figure 1.1: Orbital Maneuvering Vehicle



The OMV is to be a remotely controlled, free-flying vehicle. It will be about 15 feet in diameter and 6 feet thick and will weigh 19,200 pounds with a full load of fuel.

The OMV is to have three propulsion systems: a main propulsion system to provide the vehicle's primary thrust, a reaction control system to provide the control needed to maneuver and guide the vehicle, and a cold gas system to propel the vehicle when it is operating close to satellites that are very sensitive to contamination. The OMV will have its own thermal, electrical, guidance, navigation, control, data management, and communications subsystems. The OMV is designed to be carried to orbit inside the shuttle's cargo bay. Once separated from the shuttle, it will be remotely controlled by astronauts working at consoles on earth.

In a typical satellite reboost mission, the OMV will first be removed from the cargo bay by the shuttle's remote manipulator arm. After the shuttle moves a safe distance from the OMV, the ground-based OMV operators will remotely ignite the vehicle's propulsion system and provide the commands needed to guide it to the general area of its target satellite. Upon arrival at the approximate rendezvous area—about 3 miles behind and 1 mile below the target—the OMV's on-board radar will seek the precise satellite location. When the OMV is about 1,000 feet from its target, a television camera and floodlights aboard the vehicle will be switched on, and the earth-based operators will begin a slow docking maneuver. Just before docking, the relative speed between the vehicle and its target satellite will be extremely slow—perhaps only an inch or less per second. Once docking is accomplished, the operators can guide the OMV and the satellite to its destination and then return the OMV to the shuttle.

After each mission, the shuttle will return the OMV to earth, where it will be refurbished and stored for use on future flights. With refurbishment, the OMV is expected to last 10 years.

Program History

The OMV's conceptual design has evolved over a number of years. NASA planned to use its predecessor, the Teleoperator Retrieval System, to reboost Skylab to a safe orbit, but it terminated the program in 1978 when Skylab reentered the earth's atmosphere earlier than expected. NASA then redefined the concept to make the vehicle more versatile. From 1983 through 1985, NASA and three contractors conducted studies and analyses to define a preliminary design for the OMV.

The detailed design and development phase began in November 1986 when NASA selected TRW, Incorporated, as the OMV prime development contractor. The cost-plus-award-fee contract with TRW provides for the design, development, test, verification, and delivery of one OMV flight vehicle and associated support equipment. It also includes mission support for the OMV's development test flight and refurbishment of the vehicle following that flight. The contract contains options for production of a second OMV flight vehicle and mission support for up to nine additional OMV flights.

In mid-1989, TRW notified NASA that it anticipated overrunning negotiated contract costs. Following the disclosure, NASA decided to restructure the program. Both TRW and NASA strengthened program management and reduced the scope of the development contract to lessen cost and technical risks. The scope reductions simplified the vehicle's design but also reduced its planned capabilities. In addition, NASA and TRW agreed in principle to change the contract fee structure. The contract originally provided for a base fee and a variable award fee determined by NASA's periodic evaluations of TRW's contract performance. The parties had agreed to eliminate the base fee and make all future fee payments contingent on NASA's periodic award fee evaluations. The conversion of the contract to an all award-fee contract was never officially finalized.

NASA also decided to revise the program schedule, stretching the development program out by 18 months because of fiscal year 1990 and 1991 funding limits. The OMV's first launch, originally planned for April 1990, was scheduled for April 1995.

Program Costs

NASA estimated that OMV development would cost $736.5 million. Through fiscal year 1990, the Congress has appropriated $245.6 million. NASA requested another $85.4 million for OMV in its fiscal year 1991 budget.

Program Management

The OMV is being developed under NASA's Office of Space Flight. The Marshall Space Flight Center, NASA's lead center, is responsible for total OMV program management. Marshall is also responsible for the design, development, test, and evaluation of the OMV flight vehicle and its ground support equipment, airborne support equipment, payload accommodations equipment, and ground control console. The Johnson Space Center is responsible for activities associated with integrating the OMV and its payloads into the space shuttle and for OMV flight operations. The Kennedy Space Center is responsible for launch and landing activities.

Objectives, Scope, and Methodology

We reviewed the OMV program at the request of the Chairman, House Committee on Science, Space, and Technology. Our objectives were to determine (1) whether NASA had established a firm need for the OMV and (2) why the program's costs had increased.

To determine if NASA had established a firm need for the OMV, we reviewed NASA studies, reports, and briefings that addressed uses for and alternatives to the OMV. We discussed potential uses and benefits of the vehicle with OMV program officials at NASA Headquarters, Marshall Space Flight Center, Johnson Space Center, and TRW. We also interviewed managers of NASA and Department of Defense programs identified as potential OMV users to determine their requirements for the vehicle and other alternatives for accomplishing the missions. These included officials of the Hubble Space Telescope, Advanced X-ray Astrophysics Facility, Gamma Ray Observatory, Satellite Servicing System, Space Station Freedom, Earth Observing System, Waves in Space Plasma, Mars/Lunar Initiative, Shuttle-C, and Survivable Power Subsystem programs.

To determine the reasons for program cost growth, we reviewed internal NASA program, contract, and budget documents and contractor cost reports. We also discussed the reasons for cost growth with NASA and TRW program officials.

We reviewed the OMV program from August 1989 through April 1990 in accordance with generally accepted government auditing standards.

Chapter 2

NASA Has Not Established a Firm Need for the OMV

NASA does not need the OMV to accomplish the primary missions for which it was designed. In late 1989, NASA reduced or eliminated a number of the vehicle's planned capabilities to contain growing costs. The designated missions of the OMV were to reboost the Hubble Space Telescope (HST) and deploy and reboost the Advanced X-ray Astrophysics Facility (AXAF). NASA can accomplish these missions with the shuttle at less cost than the continued development and operation of the OMV. Furthermore, requirements for other potential missions using the OMV are uncertain, and most of these missions cannot be completed with the currently configured OMV.

Program Restructuring Reduced OMV's Capabilities

As originally conceived, the OMV was to be used as a multipurpose space tug for a number of satellites. It was to transport payloads or satellites to and from the shuttle or space station and other orbits, reboost them when their orbits decayed, retrieve and return them when they malfunctioned, examine payloads to help determine whether and why they malfunctioned, and control their reentry into the atmosphere when their useful lives expired. In 1989 NASA restructured the program to contain escalating costs. Many of the OMV's planned capabilities were reduced or eliminated in the restructuring. NASA was designing the OMV in such a way that these capabilities could be restored later, if needed. Table 2.1 shows the major OMV performance characteristics and the effects of the restructuring.

Table 2.1: Status of Major OMV Performance Requirements

Performance requirement	Eliminated	Reduced	Unchanged
Missions			
Deliver payloads		X	
Retrieve payloads		X	
Reboost payloads		X	
Deboost payloads[a]		X	
View payloads[b]		X	
OMV Basing and Control			
Shuttle based			X
Space station based	X		
Space based[c]	X		
Ground controlled			X
Station controlled	X		
Automatic navigation to payloads	X		
Manned control during final docking			X
OMV Operations			
Cold gas propulsion[d]			X
Low "G" trajectory[e]			X
Contingency return of payloads	X		
Accommodation of various enhancements		X	
Payload Accommodations			
Provide limited resources to payloads	X		
3-point docking system			X
1-point docking system	X		
OMV Maintenance			
On-orbit maintenance	X		
10-year refurbishment			X

[a] Deboost - controlling the angle and location at which a satellite reenters the Earth's atmosphere

[b] Viewing - flying around satellites to examine them for possible malfunctions.

[c] OMV was to have been capable of parking in orbit for up to 9 months between missions.

[d] Cold gas propulsion is needed to avoid contaminating some payloads, such as the Hubble Space Telescope.

[e] Low "G" trajectory means very low acceleration.

Scaling down the OMV's capabilities limited the missions it would be able to accomplish. Because of changes in its propulsion, electrical power, and guidance systems, the OMV would not be able to deliver, retrieve, or reboost payloads as far as originally planned. It would not be able to deboost as large a payload as originally planned.

The reductions were most dramatic in the delivery and deboost missions. For example, the distance the OMV could transport a 3,500-pound satellite in an initial delivery mission was reduced by 60 percent.[1]

The shuttle alone can deliver large payloads into space more efficiently, according to a recent assessment by the Johnson Space Center. This study showed that the shuttle can deliver payloads weighing more than 9,000 pounds to higher orbits than the shuttle-OMV combination could deliver them. With the combined weight of a payload and the 19,200-pound OMV, the shuttle's initial orbiting altitude will be lower, and the reduced-capability OMV would not be able to make up for the lower shuttle altitude.

Also, the reduced-capability OMV would not be able to control the reentry of large payloads, whose fall to earth may present a safety hazard. The full-capability OMV was expected to be able to deboost payloads weighing up to 75,000 pounds; the reduced-capability OMV would not be able to deboost payloads weighing more than 15,000 pounds. NASA currently has no requirement to deboost payloads weighing less than 15,000 pounds, since objects of this size and smaller normally burn up during reentry into the Earth's atmosphere, according to the NASA headquarters OMV Program Manager.

NASA would not be able to base the reduced-capability OMV at Space Station Freedom and control it from that location or to leave the vehicle in space between missions. Therefore, the OMV would have to be transported to and from each mission on the shuttle.

The reduced-capability OMV would not be able to automatically navigate to its payload as was originally planned. Ground controllers would have to guide it during the entire flight sequence. As a result, the time needed to track a target payload increased from 5 minutes to about 3 hours. Two additional ground-based flight controllers would be needed to generate data for the tracking.

The reduced-capability vehicle would not be able to provide resources such as communications or power to its payloads except for rare instances when payloads would be hard-wired to the OMV. Also, one of two planned docking mechanisms was eliminated from the vehicle design during the restructuring. As a result, the OMV would not be compatible with some payloads that might be carried on the shuttle.

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[1] The reduction was from 340 nautical miles to 136 nautical miles, assuming a 1-degree change in the satellite's orbital inclination.

Originally, the OMV was to have been repaired while in orbit by astronauts who would have worked from Space Station Freedom to remove and replace groups of components called "orbital replacement units." The reduced-capability OMV would not have orbital replacement units. If it malfunctioned while in space, it would have to be returned to earth for repairs.

According to NASA officials, the OMV was designed so that capabilities eliminated in the restructuring could be restored to the vehicle if they were needed. Space would be reserved in the vehicle to restore the capabilities, and any needed couplings would be built.

OMV Not Needed for Scheduled Missions

The reduced-capability OMV is being designed primarily to deploy the AXAF and reboost the AXAF and HST as their orbits decay. Recent NASA studies show, however, that the vehicle is not needed to perform these missions. The cost of using only the shuttle for these missions is lower than the cost of continued development and operation of the OMV.

Shuttle Can Deliver AXAF Without OMV

Under NASA's current schedule, the shuttle will be able to deploy the AXAF observatory without OMV's assistance. Advanced solid rocket motors needed for the shuttle to deliver the AXAF to its required altitude are scheduled to be available more than a year before the planned 1997 launching of the observatory.

To avoid having to reboost the AXAF for at least 5 years, NASA would like to deliver it to an initial orbital altitude of 320 nautical miles. Altitudes of large satellites in low earth orbit decay over time due to drag, which is influenced by activity on the sun. The observatories' abilities to collect scientific data could be adversely affected if their orbits are allowed to get too low, especially during periods of high solar activity. As a result, NASA expects that the observatories may have to be reboosted to higher orbits from time to time. However, at an initial altitude of 320 nautical miles, NASA estimates that it should not be necessary to reboost the AXAF during its first 5 years on orbit.

NASA officials once believed that the OMV was needed to get the AXAF to an altitude of 320 nautical miles. With its current solid rocket motors, the shuttle will not be able to deliver the 32,800-pound AXAF to an orbital altitude higher than about 270 nautical miles. A February 1990 performance assessment by the Johnson Space Center showed, however, that the shuttle cannot carry both the AXAF and OMV into orbit on the same flight. The assessment also showed that with the advanced solid rocket motors, expected to be available in December 1995, the shuttle can carry AXAF to an initial orbit of 320 nautical miles without the OMV. The OMV will not be needed for AXAF deployment if the shuttle's advanced solid rocket motors are available as scheduled.

If NASA cannot maintain the schedule for the advanced solid rocket motors and they are not available when AXAF must be launched, NASA could launch the observatory on a shuttle with currently designed motors and boost it to a higher orbit later. Either the shuttle or the OMV could provide the boost. Without the OMV, two shuttle flights would be needed to boost AXAF to its desired altitude of 320 nautical miles; with the OMV, only one flight would be needed. If the OMV were used, it could be carried into space prior to the AXAF being launched, or the OMV could be launched after the AXAF deployment to boost the observatory to its desired orbit. However, the OMV's current design would have to be modified to allow it to remain in space for several months.

Shuttle Can Reboost Observatories at Lower Cost

Recent NASA studies show that the shuttle can reboost the HST and AXAF observatories without the OMV. By reboosting the observatories a little during each scheduled maintenance visit, only one or two shuttle flights dedicated to reboosting the observatories should be required to keep them at sufficiently high altitudes even under worst-case conditions, according to the studies. The two dedicated shuttle flights would be less costly than continued OMV development and operation.

NASA plans for the shuttle to revisit HST and AXAF periodically to maintain them and to replace their scientific instruments. Current plans are to revisit the HST every 3 years for maintenance and every 5 years for instrument replacement. One new scientific instrument is already under development and should be available for incorporation into the HST in 1995. AXAF is to be revisited every 5 years for servicing and refurbishment.

Two space studies show that the shuttle will be able to keep the observatories at acceptable altitudes even without the OMV. According to a September 1989 Johnson Space Center study, the shuttle can reboost the HST a little on each scheduled maintenance mission and keep it at a sufficiently high altitude through the turn of the century. If solar activity is especially high near the turn of the century, one additional flight might be needed to reboost HST to a sufficiently high altitude. However, according to the study, the telescope will not have to be reboosted if solar activity is at an average level.

In a similar study completed in March 1990, NASA's Office of Space Flight concluded that one or two additional shuttle flights might be required early in the next century to reboost the observatories without the OMV. One flight dedicated to reboosting AXAF would be needed in 2000 and one flight dedicated to reboosting HST would be needed in 2001. All other reboost requirements could be accomplished during planned maintenance and refurbishment missions.

These two shuttle flights are a less costly way of reboosting the observatories than continued development and operation of the OMV. The marginal costs of two shuttle flights in fiscal years 2000 and 2001 together with the cost of terminating the OMV program would be about $277 million. The cost of completing the OMV development, conducting the development test flight, storing the vehicle at Kennedy, and operating it for the two flights would cost over two and one-half times that amount—an estimated $716 million. The two estimates are shown in table 2.2.

Table 2.2: Costs of Options for Reboosting HST and AXAF Observatories

Dollars in millions

Cost category	Shuttle only	Shuttle with OMV
Complete OMV development	[a]	$529.50[b]
OMV termination cost	$79.40	
Shuttle flight for OMV development test (1995)[c]	[a]	77.50
OMV storage (1996-99)	[a]	17.60
Shuttle flight to reboost AXAF (2000)[c]	96.60	[a]
OMV flight to reboost AXAF	[a]	44.88
Shuttle flight to reboost HST (2001)	100.95	[a]
OMV flight to reboost HST	[a]	46.90
Total	**$276.95**	**$716.38**

[a] Not applicable.

[b] The current cost estimate to complete OMV development is $736.5 million less costs expected to be incurred through June 30, 1990, ($207 million).

[c] The shuttle flight costs are the marginal cost of a 1995 flight, the last year for which NASA has projected shuttle flight costs. Marginal costs are the incremental costs for adding one additional shuttle flight in each of the years. These costs do not include fixed costs associated with shuttle flights, which NASA will incur whether or not additional flights are undertaken.

Future Mission Requirements Are Uncertain

According to NASA's Office of Space Flight, the OMV is needed not only for delivery and reboost of HST and AXAF but also as a part of the nation's overall space transportation infrastructure. However, NASA has not yet decided to undertake any of the missions it has identified as potential applications for the OMV. Furthermore, the currently configured OMV would not be able to perform the missions even if they were approved. The potential missions include (1) carrying supplies and materials from expendable launch vehicles to Space Station Freedom, (2) serving as the propulsion module for the station's assured crew return vehicle, (3) transporting equipment and supplies from expendable launch vehicles to the station's Polar Orbiting Platform, (4) transporting automated satellite servicing equipment, and (5) providing a contingency capability in the event of another shuttle accident.

Using expendable launch vehicles with the OMV to resupply Space Station Freedom would reduce requirements for the space shuttle, according to officials of NASA's Unmanned Launch Vehicles and Upper Stages Branch of the Office of Space Flight. The OMV could be used to transfer the supplies from the expendable launch vehicles, which would be parked 20 nautical miles away, to the station. Similarly, the OMV could be used to transfer to and from the station materials needed for any manned missions to the moon and Mars. According to NASA, the OMV would have to be modified so that it could be based either at the station or in space, and the amount of propellant it could carry would have to be increased to accomplish these missions. Neither of the missions has been approved. NASA currently plans to use the manned shuttle to resupply all of the station's needs. No decision has been made on ways to accomplish any manned missions to the moon and Mars. Also, NASA may have alternatives to using the OMV for these missions. At least one firm is interested in providing commercial launch services for station resupply. This firm maintains that it could deliver the supplies and materials to the station.

The OMV development contractor has proposed using the OMV to return a crew from Space Station Freedom to Earth in an emergency. However, the OMV's design would have to be modified to permit the vehicle to be based at Freedom and to increase its propulsion capabilities. NASA is currently studying various ways of returning crews from Freedom but does not plan to select a crew return vehicle design until 1994.

According to OMV program officials, the OMV could be used with expendable launch vehicles to resupply the polar orbiting platform, which is planned as part of NASA's Earth Observing System. However, according to a program official, it would not be cost-effective to design the polar orbiting platform so that it could be resupplied. Even if NASA later decided to include the capability to resupply the polar orbiting platform in its design, the currently configured OMV could not be used in the resupply operation. The OMV would have to be modified to make it compatible with expendable launch vehicles and enable it to be based in space or at the platform. Also, another OMV would have to be purchased for this mission, since the space shuttle cannot go to polar orbit, and the OMV could therefore not be retrieved from the platform.

The OMV might also be used to transport automated satellite servicing equipment if development of that equipment is approved. NASA is currently studying designs that would enable it to maintain satellites in orbit by robotically replacing component modules and refueling the satellites. If developed, the satellite servicing system could be attached to the OMV. However this system is not expected to be available before 2000, potential servicing missions have not been defined, and robotically serviceable satellites do not currently exist. Also, the OMV's design would have to be modified to enable it to be used with the satellite servicing system.

OMV program officials also have stated that the vehicle could be used if the shuttle were to become incapacitated. For example, the OMV and expendable launch vehicles could resupply the station if the shuttle were not available for a long period. However, the OMV would have to be modified so that it could be launched on an expendable launch vehicle.

Estimated OMV Costs Have Continued to Increase

OMV's estimated costs have substantially increased due to schedule stretch-outs, program content changes, and contract cost growth. Further increases are likely because the OMV is in an early stage of development, reserves to cover future program changes are less than NASA normally includes in its estimates, and system enhancements are needed for OMV to perform some of its potential missions. Program acquisition costs could also increase to about $1.3 billion if NASA restores the capabilities eliminated from the OMV's design, purchases a second vehicle, makes the two vehicles compatible with expendable launch vehicles, and purchases an initial contingent of spare parts. NASA has not yet prepared a complete estimate of operational phase costs but has estimated the costs of certain specific missions.

Program Costs Have Grown Substantially

Since OMV development was approved in 1986, estimated program costs have increased about 82 percent, from $405.0 million to $736.5 million. At the same time, the vehicle's capabilities have been significantly reduced. The program estimate would have been about $890.0 million if NASA had not reduced the estimate by about $154.0 million by eliminating some of the OMV's capabilities and paring cost reserves. Table 3.1 shows the cost changes.

Table 3.1: Changes in OMV Cost Estimates

Dollars in Millions

Cost changes	Amount
Increases	
Schedule stretch-outs	$256.1
Program changes	105.9
Contract cost growth	123.1
Subtotal of increases	**$485.1**
Decreases	
Reduced technical capabilities	−$81.5
Reduced cost reserves	-72.1
Subtotal of reductions	**- 153.6**
Net change	**$331.5**

According to NASA, schedule stretch-outs resulting from internally imposed budget cuts are the primary cause of the cost increases to date. NASA has reduced the OMV budget in each of the last 4 years to fund higher priority programs. The budget reductions meant that work had to be postponed and the development program delayed. The stretch-outs have added 5 years to the OMV's development program. The schedule for the vehicle's first flight slipped from April 1990 to April 1995. Schedule stretch-outs increased OMV costs over $256 million.

According to NASA and TRW officials, the primary lesson to be learned from the OMV program is that a project started without a firm, near-term requirement is likely to "become the bank" for programs with more immediate funding needs. Because no other program is dependent on the availability of OMV, NASA reduced its budget and stretched out development to provide more funds for other, more urgently needed programs.

Program changes added about $106 million to estimated costs. A primary change was associated with moving responsibility for OMV operations from the Marshall Space Flight Center to the Johnson Space Center. When the program was initially approved, the Marshall Space Flight Center was assigned responsibility for both development and operations. Soon after the contract was signed, however, NASA decided to shift responsibility for OMV operations to the Johnson Space Center. Officials at Johnson concluded that developing the hardware and software for OMV operations and operator training would cost about $69 million more than previously estimated. Various other program changes added another $37 million to the estimate. These included, for example, changes resulting from the vehicle's preliminary design review.

Contract cost growth accounts for an increase of over $123 million, of which $75 million was for the prime contractor's work and $48 million was for estimated subcontract costs. According to the previous OMV Program Manager, TRW's original contract price of $212 million underestimated OMV development costs. TRW agreed that its original contract price was too low because it had made optimistic assumptions. For example, TRW had assumed that it would not have to develop unique components for the OMV but instead could use some off-the-shelf hardware. TRW also believed that the frequency of OMV schedule changes contributed to its inability to estimate prices.

The program cost estimate would have been even higher if it had not been offset in part by contract scope reductions in 1989 and reductions in cost reserves. The reductions in scope included simplifying the OMV's design and decreasing its planned capabilities. Spare parts and some tests and documentation were also deleted. In addition, NASA also reduced the amount of reserves contained in the estimate to absorb future cost increases. The estimate just prior to the program restructuring contained reserves equal to about 34 percent of the future development costs. Reserves in the current estimate are equal to about 15 percent of the remaining development costs.

Further Cost Increases Are Likely

OMV costs will likely continue to rise, especially if NASA is to make maximum use of the vehicle. The program is still in an early design phase, and reserves to cover future cost increases are significantly less than NASA normally includes in its program cost estimates. Further, to complete some potential missions, NASA would have to modify the OMV by restoring some capabilities previously deleted and adding a new capability—delivery of the OMV by expendable launch vehicles. NASA may also have to purchase an additional vehicle and the spare parts needed for maintenance.

Adequacy of Cost Reserves

The OMV development program is less than half complete, and those same factors that caused cost increases in the past could also cause future cost increases. The $736.5 million estimate includes a $72.6 million reserve to absorb future cost increases, but that amount is only about half the amount NASA normally budgets for programs at this stage in development, according to the Chief of the Cost and Economic Analysis Branch, NASA Comptroller.

The OMV program could experience more of the same type of budget cuts that have already caused schedule stretch-outs and added $256.1 million to the program's cost. NASA's Associate Administrator for Space Flight told the Subcommittee on Space Science and Applications, House Committee on Science, Space, and Technology, in February 1990 that if NASA has to make budget cuts in fiscal year 1991, the "OMV would not be immune to its fair share of the cuts." In this regard, NASA's fiscal year 1991 budget request of $15.1 billion represents a 23-percent increase over fiscal year 1990, and the agency projects that its budget requirements will increase by another 17 percent in fiscal year 1992 and an additional 10 percent in fiscal year 1993. With projected increases of this magnitude, cuts in NASA's budget requests are a distinct possibility as Congress attempts to address the deficit and other pressing fiscal issues over the next several years.

More design changes are also to be expected. The program's critical design review is not scheduled until April 1991. Following the design review, the contractor will begin hardware fabrication and testing.

Design changes are to be expected as a result of the design review and fabrication and testing activities. According to the Chief of NASA's Cost and Economic Analysis Branch, most cost increases occur during a program's hardware fabrication and testing phases. According to this official, it is not unusual for development programs to take longer than planned because of problems identified during testing of complex components such as electronic assemblies.[1] Extending a program increases its cost.

Other contract cost increases are also possible, particularly in subcontracts. Subcontract costs in the $736.5 million estimate, are for the most part not based on negotiated prices or firm proposals from the subcontractors. Through February 1990, firm prices had been negotiated for only about 65 percent of the subcontracts. Also, TRW did not have proposals from subcontractors detailing the cost impact of the most recent program stretch-out. According to Marshall's Deputy OMV Project Manager, NASA believes that the current estimate for subcontracts is adequate, but it cannot be certain of that until firm proposals are received and negotiated.

The $72.6 million cost reserve included in the estimate is less than half the amount NASA normally includes in program estimates prior to critical design review. The reserve, or allowance for program adjustment, is intended to absorb cost increases that may occur in the future. According to the Chief of NASA's Cost and Economic Analysis Branch, NASA would normally include in the estimate a cost reserve equal to about 30 percent of future costs for such a complex program prior to its critical design review. The OMV reserve is only about 15 percent of future costs.

According to the Deputy OMV Project Manager, when NASA restructured the development program in 1989, it reduced the OMV's cost and technical risk. The Deputy Project Manager concluded that, in total, the cost reserves would be adequate, but amounts available in fiscal years 1990 and 1991 would be marginal. If costs were to increase significantly in these years, work would have to be deferred and the schedule might have to be delayed again.

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[1] There is a 4-month cushion built into the OMV program to accommodate schedule changes during the fabrication and testing phase.

Future Program Enhancements

NASA is considering purchasing an additional vehicle, restoring capabilities, and modifying the OMVs to make them compatible with expendable launch vehicles. According to preliminary NASA estimates, these actions, together with an initial contingent of spare parts for the two vehicles and a spare propulsion module could add another $540.6 million to the OMV's acquisition cost, raising the total for two OMVs to about $1.3 billion. NASA considered that the additional costs, if required, would be a part of the vehicle's operational, rather than the developmental program. Table 3.2 shows the potential additional acquisition costs.

Table 3.2: Potential Additional OMV Acquisition Costs

Dollars in millions

Cost Category	Cost
Restored capabilities	$112.7
Second OMV	303.8
Expendable launch vehicle compatibility	25.2
Spare parts	69.3
Spare propulsion module	29.6
Total	**$540.6**

Modifying the OMV would cost about $112.7 million, according to a preliminary NASA estimate. This estimate assumes that the OMV would be modified to restore its full capabilities after NASA purchased a second OMV with full capabilities. Another $25.0 million would be needed to design, develop, and qualify the modifications if NASA did not purchase a second vehicle.

NASA estimated that a second, full capability OMV could be purchased for about $303.8 million if production of the vehicle were authorized for fiscal year 1993. The vehicle would be delivered in May 1998.

Modifying the two OMVs to make them compatible with expendable launch vehicles such as the Titan IV would cost an estimated $25.2 million. Purchasing the initial contingent of spare parts and components needed to maintain the vehicles would cost another $69.3 million between fiscal years 1993 and 1996. A spare propulsion module, which might be needed if the OMV were based at Space Station Freedom, would cost an estimated $29.6 million.

NASA considers it unlikely that it would do all of these things. The agency described them as "an accumulation of various possible options that represent a worst case scenario that probably would never materialize."

OMV Operational Costs

Because of uncertainty about when and for what purposes the OMV would be used, NASA has not prepared a comprehensive estimate of OMV operations costs. Instead, the agency estimated operation costs for two alternative mission scenarios.

Both scenarios involve reboosting the HST in mid-1996 and boosting the AXAF to its desired altitude when it is deployed in 1997. In the first scenario, the OMV would be carried into space and left there to await AXAF deployment. In the second scenario, the AXAF would be launched first and the OMV brought up later to boost the observatory to its final altitude. NASA estimated that the first scenario would cost about $90.1 million, while the second would cost about $81.7 million. Both estimates include costs to (1) store the OMV following its 1995 test flight; (2) remove the OMV from storage, prepare it for launch, and reboost the HST with it in June 1996; (3) refurbish the OMV following the HST reboost; (4) launch and operate the OMV to boost AXAF to its final destination in 1997; and (5) refurbish the OMV and place it in storage to await some future mission. The primary difference between the two estimates is that the first scenario includes the cost of adding gallium arsenide solar arrays to equip the OMV for space basing.

NASA also estimated the annual recurring cost of storing the OMV between missions and the operation cost for a typical reboost mission. Both of these estimates are in constant fiscal year 1990 dollars, since it is not known when the reboost mission would occur or how long the vehicle would have to be stored between missions. NASA estimated that $3.2 million a year would be needed to store the OMV and that an additional $28.9 million would be needed for a typical reboost mission.[2]

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[2] OMV storage and operations shown in table 2.2 on page 21 are based on these estimates, but the amounts in the table include an allowance for future inflation of 4.5 percent a year for each year after 1990.

Chapter 4

Conclusions, Recommendation, Matter for Congressional Consideration, and Agency Comments

Conclusions

NASA has not adequately justified or established a need for the OMV. The vehicle's two scheduled missions can be accomplished by other means that cost less. Furthermore, although NASA has identified other potential missions for the vehicle, these missions have not been approved and no requirements have yet been firmly established for them. Even if these missions were approved, the OMV would have to be modified, at additional cost, before it could be used for them.

Because NASA has not had a firm need for the OMV, it has been a target for budget cuts that have proved to be costly to the OMV program. Faced with more pressing needs and not enough funds, NASA officials have reduced the program's funding in each of the last 4 years to fund higher priority programs that had firmer requirements. Most of the OMV's cost increase can be attributed to schedule delays.

Further cost increases are likely, especially if NASA is to make maximum use of the vehicle. Schedule delays, program changes, and cost growth have already caused development costs to nearly double. These same factors could cause further increases, since it is still early in the OMV's development stage, and reserves to cover future cost increases are only about half the amount NASA normally budgets in cost estimates of similar programs. Also, OMV program acquisition costs could increase to $1.3 billion if NASA decides to (1) restore all of the vehicle's originally planned capabilities, (2) purchase an additional vehicle, (3) make the two vehicles compatible with expendable launch vehicles, and (4) purchase an initial contingent of spare parts.

A primary lesson learned from the OMV program is that a development program should not be started before a firm requirement is established. Once started, the program should be funded so that it can be conducted expeditiously and efficiently.

Recommendation and Agency Action

In our draft report we recommended that the Administrator terminate the OMV program. NASA estimated that it had already spent $199.4 million on the program through June 6, 1990, and that an additional $79.4 million[1] would be required for termination. However, the remaining $450.1 million cost to complete the development and any additional costs for restoring capabilities eliminated in the 1989 restructuring, procuring a second vehicle, and operating the vehicles would be avoided if the program were terminated.

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[1] The $79.4 million required for termination includes $46.2 million in fiscal year 1990 funds and $33.2 million in fiscal year 1991 funds.

NASA terminated the OMV program and instructed TRW to cease all work under the contract 6 days after receiving our draft report. The agency cited budgetary pressures and the lack of a firm, near-term requirement for the vehicle as reasons for the termination.

Matter for Congressional Consideration

The Congress should deny the $85.4 million requested for OMV development in fiscal year 1991, less any amount needed for termination expenses. According to a preliminary NASA estimate, about $33.2 million of fiscal year 1991 funding will be needed for termination.

Agency Comments

We incorporated NASA's comments into this report where appropriate.

Major Contributors to This Report

National Security and International Affairs Division, Washington, D.C.	Charles Rey, Assistant Director James Morrison, Evaluator
Atlanta Regional Office	Lee Edwards, Evaluator-in-Charge Mark Lambert, Site Senior Karen Lindsey, Evaluator

United States General Accounting Office

GAO

Report to the Administrator, National Aeronautics and Space Administration

August 1990

SPACE PROGRAM SAFETY

Funding for NASA's Safety Organizations Should Be Centralized

GAO

**United States
General Accounting Office
Washington, D.C. 20548**

**National Security and
International Affairs Division**

B-239537

August 16, 1990

The Honorable Richard H. Truly
Administrator, National Aeronautics
and Space Administration

Dear Admiral Truly:

We have completed our review of the National Aeronautics and Space Administration's (NASA) safety-related programs. We reviewed the programs to determine whether NASA had established an independent organization with direct authority for these programs throughout the agency, as recommended by the Presidential Commission on the Space Shuttle *Challenger* Accident.[1]

Background

In the aftermath of the space shuttle *Challenger* accident, the President appointed a commission to review the circumstances surrounding the accident, establish the probable cause or causes, and develop recommendations for corrective action. The Commission's report criticized NASA for its "silent safety program."

The Commission concluded that NASA did not have an independent and effective safety organization. The Chief Engineer at NASA headquarters had overall responsibility for safety, reliability, and quality assurance, but his ability to manage the program was restricted by organizational structure and limited staffing. Safety activities at field centers were subordinate to the projects and activities they were intended to oversee. For example, at Marshall Space Flight Center, the Director of Reliability and Quality Assurance reported to the Director of Science and Engineering, who was responsible for overseeing the development of space shuttle hardware.

According to the Commission, this arrangement resulted in the safety organization's lack of necessary independence from the hardware producer. This lack of independence in turn reduced the safety organization's capability to serve as a watchdog to ensure that sound engineering judgment was exercised in using hardware and in analyzing hardware problems. According to the Commission, an effectively functioning safety, reliability, and quality assurance organization could have taken action to prevent the Challenger accident.

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[1] *Report of the Presidential Commission on the Space Shuttle Challenger Accident*, (Washington, DC: June 6, 1986), p. 199.

Among other things, the Commission recommended that NASA establish a safety, reliability, and quality assurance office that would (1) be headed by an Associate Administrator, who would report directly to the NASA Administrator; (2) have direct authority for safety, reliability, and quality assurance throughout the agency; and (3) be independent of other NASA functional and program responsibilities.

In July 1986, NASA responded to the Commission's recommendations by creating the Office of Safety, Reliability, Maintainability, and Quality Assurance (SRM&QA).[2] In addition, it reorganized safety activities at its field centers and provided them with increased resources. The SRM&QA organization is responsible for providing independent oversight, review, assessment, and approval of all NASA's safety-related activities.

According to SRM&QA documents, NASA plans to spend over $500 million in fiscal year 1990 for SRM&QA activities. Most of this amount is to be spent on prime contractors' efforts to ensure the quality and safety of products they are developing for NASA.

Results in Brief

In response to the recommendations of the Presidential Commission on the Space Shuttle Challenger Accident, NASA established the Office of SRM&QA to provide independent oversight of all safety-related activities. This office is headed by an Associate Administrator and reports directly to the NASA Administrator. Field center safety organizations report to center directors but have access, as needed, to the Associate Administrator for SRM&QA.

We found that, while this organizational structure appeared adequate, field center safety organizations were not entirely independent because they obtained most of their funds from activities whose safety-related performance they were responsible for overseeing. The center safety organizations obtained over 90 percent of their fiscal year 1990 budgets—about $124 million—from the offices whose projects were subject to the center safety organizations' oversight and from the headquarters offices that supervised those projects.

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[2] On May 1, 1990, the name of this office was changed to the "Office of Safety and Mission Quality."

We do not believe that this method of funding enables NASA's safety organizations to maintain the complete independence envisioned by the Presidential Commission. While we found no evidence that such heavy reliance on project offices for funding had compromised the safety programs' effectiveness, the potential for reduced effectiveness exists. Also, NASA officials do not agree on the most appropriate method of budgeting and funding SRM&QA activities. Most of the field centers' officials expressed concern about the effect of current funding processes on the independence of their SRM&QA organizations.

Current Funding Process Limits Independence

Of the over $500 million budgeted for safety-related activities, about $124 million is for the field center safety organizations. These organizations use their funds primarily to pay mission support contractors.[3] However, field center safety organizations must rely on three separate sources for funding: (1) the headquarters SRM&QA office, (2) center project offices, and (3) the headquarters offices that supervise the projects.

The process for funding NASA's field center safety organizations limits their independence because they receive most of their funds from offices whose projects they oversee. Center safety organizations also receive funds from the headquarters offices through a multiple program support process.[4] Consequently, center SRM&QA activities could be underfunded, and the flexibility of center safety oversight could be restricted. While not all NASA officials agree, most center officials expressed concern that the current funding process could compromise independence or result in an inadequately funded SRM&QA program.

Further, NASA does not have one standard process to budget for SRM&QA activities. At the Goddard Space Flight Center, for example, programs provide some funds directly but also are taxed a percentage of their budgets to support generic SRM&QA activities at the center. The percentage is based on the number of civil service employees assigned to the project.

On the other hand, the Marshall Space Flight Center's SRM&QA officials and project representatives negotiate the amount of center project funds to support Marshall's safety organization. The Marshall safety organization also obtains multiple program support funds from the headquarters office of Space Flight's engineering and technical base budget. In fiscal year 1990, for example, the headquarters Office of SRM&QA provided a relatively small amount—$1.1 million—to Marshall Space Flight Center and earmarked it for specific tasks rather than for support of Marshall's general SRM&QA mission. About 92 percent, or $12.3 million ($13.4 million minus $1.1 million), of Marshall's fiscal year 1990 SRM&QA funds came from both the project offices whose projects the center SRM&QA office was to oversee and the headquarters offices that supervised those projects. Figure 1 illustrates the funding sources for the Marshall Space Flight Center's SRM&QA activities in fiscal year 1990.

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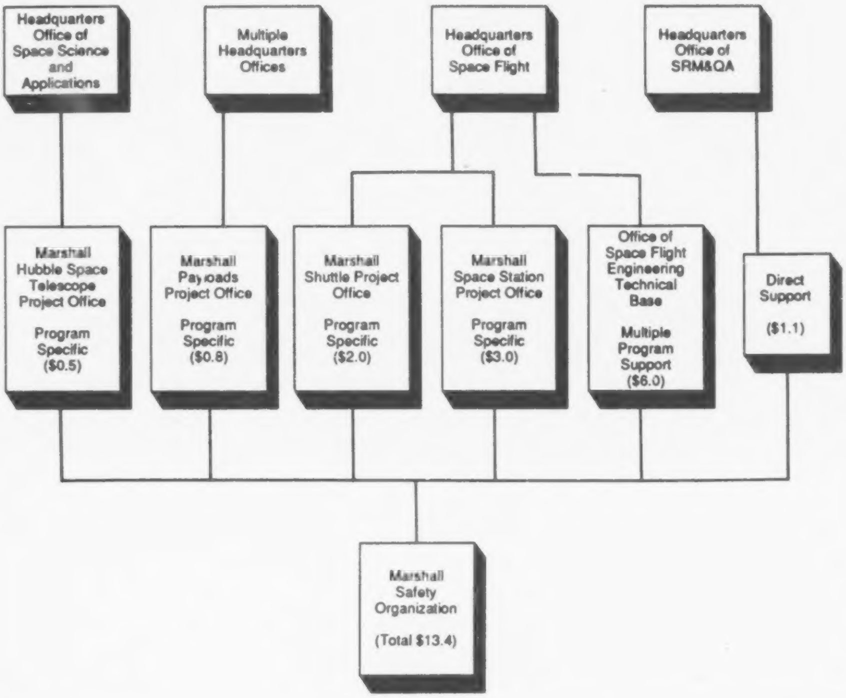
[3] Mission support contractors provide critical surveillance of design, manufacturing, and testing activities to assess compliance with policy, requirements, and controls. They also analyze and track problems and their corrective actions.

[4] As defined in this report, "multiple program support" refers to all funds provided to the centers by headquarters offices to finance common projects. These funds are classified as "engineering and technical base funds," "multiple program-support funds," and "benefits assessments funds."

Figure 1: Marshall Space Flight Center SRM&QA Funding Sources (Fiscal Year 1990)

Dollars in millions


Headquarters Office of Space Science and Applications
Multiple Headquarters Offices
Headquarters Office of Space Flight
Headquarters Office of SRM&QA
Marshall Hubble Space Telescope Project Office
Program Specific ($0.5)
Marshall Payloads Project Office
Program Specific ($0.8)
Marshall Shuttle Project Office
Program Specific ($2.0)
Marshall Space Station Project Office
Program Specific ($3.0)
Office of Space Flight Engineering Technical Base
Multiple Program Support ($6.0)
Direct Support
($1.1)
Marshall Safety Organization
(Total $13.4)

Implications of the Current Funding Process

We did not identify any instances in which the Office of SRM&QA's effectiveness was reduced because of a lack of independent funding. However, the potential for reduced effectiveness exists.

The absence of a single, independent funding source could result in the underfunding of the center safety oversight function. Center SRM&QA activities must compete for funding with research and development activities, and most of the funding is controlled by managers who are responsible for this research and development. Officials at Marshall Space Flight Center noted, for example, that the keen competition for project office funds can result in a resistance to adequately funding center safety functions. According to Stennis Space Center officials, obtaining funding from a variety of project offices is more difficult than obtaining funding from a single source.

The lack of centralized, independent funding may also restrict the flexibility of center safety managers. Officials at Johnson Space Center told us, for example, that they cannot use funds provided for a specific project or program to perform work on another project or program. As a result, they might be unable to respond promptly to changes in circumstances and priorities. These officials said that the Space Station Project Office had significantly underfunded SRM&QA activities and subsequently denied the request for additional funding. Consequently, Johnson officials used multiple program support funds from the Office of Space Flight to supplement funding for what they termed a "minimal SRM&QA program" for Johnson's Space Station Freedom work package. These officials indicated that the only reason they had been able to use multiple program support funds in this manner was that they had some discretionary control over them. However, according to these officials, their ability to continue using these funds is being impaired because the funds are frequently earmarked for specific uses.

Most NASA Safety Managers Believe That Centralized SRM&QA Funding Would Ensure Independence

Not all NASA officials agreed on the need for a centralized SRM&QA budget, even though it would ensure independent funding in meeting oversight responsibilities. However, according to the Director of Safety, Reliability, and Quality Assurance at the Johnson Space Center, in discussions at a recent SRM&QA headquarters conference, all the centers except Goddard favored a centralized source of funding for their SRM&QA organizations.

In March 1989, the Director of the Marshall Space Flight Center recommended that the agency's total SRM&QA budget be provided through the Office of SRM&QA. The Director pointed out that, while ongoing center SRM&QA programs were funded by the headquarters Office of Space

Flight and programs receiving SRM&QA support, the center needed additional SRM&QA funding. According to the Director, a separate centralized budget would provide a better focus for NASA's SRM&QA efforts.

The Director of Safety, Reliability, and Quality Assurance at the Johnson Space Center addressed the need for an independent funding source in a July 1989 memorandum to the Associate Administrator for SRM&QA. He pointed out that "he who controls the funds also determines the content of the activity." He recommended that the Office of SRM&QA fully budget all funds needed by the center safety organizations. According to this official, reliance on program funding represents the same funding arrangement that existed prior to the *Challenger* accident.

In an October 5, 1989, memorandum to the Associate Administrator for SRM&QA, the Director of Safety, Reliability, and Quality Assurance at the Kennedy Space Center expressed concern that the independent evaluation provided by safety organizations is jeopardized when critical funding is not appropriated. In this official's opinion, the headquarters SRM&QA's support for field center funding is crucial to the success of the center's safety programs. He recommended that NASA establish a process by which the safety resource requirements could be funded. The Kennedy official added that this process should include safeguards against the deletion of funds without the approval of the headquarters SRM&QA organization.

On the other hand, SRM&QA managers at the Goddard Space Flight Center told us that they do not believe that their independence is limited because they are funded by project and program offices. These officials said that they had not encountered any funding problems. They believe that project managers have primary responsibility for safety and that the use of project funds for safety oversight is consistent with that responsibility.

Conclusions

NASA has implemented the Presidential Commission's recommendation to establish separate organizations to oversee SRM&QA activities. However, because the field center safety organizations are funded primarily by the project offices whose projects they oversee and by headquarters offices that supervise those projects, they do not have the complete independence envisioned by the Presidential Commission. Although we did not identify any situations in which the existing funding process had compromised safety programs' effectiveness, the potential for reduced effectiveness exists, and the safety organizations' oversight functions could be compromised. In addition, the safety organizations could be underfunded and their flexibility impaired because they rely on this funding mechanism.

Recommendation

We recommend that the NASA Administrator modify the processes and procedures for formulating the SRM&QA budget to ensure that SRM&QA activities are funded independently of the programs and activities they are responsible for overseeing. We further recommend that the SRM&QA budget be established within the Office of SRM&QA.

Agency Comments and Our Evaluation

In commenting on a draft of this report, NASA acknowledged that since the creation of the Office of SRM&QA, a vigorous debate has ensued on the merits of centralized funding. However, NASA has chosen not to centralize funding within the Office of the Associate Administrator for SRM&QA because it could (1) lead to a lessening of the safety and mission quality responsibilities of the program managers by encouraging them to defer decisions to the Office of SRM&QA; (2) generally diminish the interaction between field center SRM&QA organizations and program offices and affect program managers, efforts to ensure that the highest priorities are addressed in the budgeting process; and (3) require a significant increase in the SRM&QA staff to properly administer the function. (NASA's comments are reprinted in app. I).

We agree that project managers should be responsible for SRM&QA and that most of the funds for SRM&QA activities are properly controlled by the project managers and provided to their prime contractors to carry out their SRM&QA responsibilities. However, the SRM&QA organization is to provide independent oversight, reviews, and assessments of how well project managers carry out their SRM&QA responsibilities. Therefore, we continue to believe that, to ensure independence, funding for these activities should be controlled by the Associate Administrator for SRM&QA and not the project managers.

We also agree that field center SRM&QA organizations should be active participants in the budgetary process and that interaction between those organizations and project offices should continue. However, in our view, trade-offs between project requirements and SRM&QA oversight requirements ought to be made at the highest levels of the organization, rather than at project office levels.

Finally, while some increase in staff to administer centralized funding might be necessary to ensure independent oversight, we question why a sizable increase would be necessary. Field center safety organization budgets are relatively small—totaling about $124 million of NASA's $12.3 billion fiscal year 1990 research and development budget—and consequently should not require a large number of personnel to administer them. Also, consolidation should offer some offsetting efficiencies both in the headquarters offices and project offices where the budgets are currently administered and in field center SRM&QA organizations where personnel now participate in multiple budget reviews each year.

Scope and Methodology

We examined the report of the Presidential Commission on the Space Shuttle Challenger Accident, internal NASA documents, and studies related to SRM&QA organization and budgeting issues. We obtained safety information on all nine space centers from NASA's SRM&QA headquarters office. In addition, we visited Marshall Space Flight Center, Johnson Space Center, and Goddard Space Flight Center to review records and interview officials to obtain their perspectives on the need for independent funding. We conducted our review from October 1989 to May 1990 in accordance with generally accepted government auditing standards.

As you know, the head of a federal agency is required by 31 U.S.C. 720 to submit a written statement on actions taken on our recommendations to the Senate Committee on Governmental Affairs and the House Committee on Government Operations no later than 60 days after the date of this report and to the House and Senate Committees on Appropriations with the agency's first request for appropriations made more than 60 days after the date of this report.

This report is also being sent to the Chairs of the Subcommittee on VA, HUD, and Independent Agencies of the House and Senate Appropriations Committee; the Subcommittee on Science, Technology and Space of the Senate Committee on Commerce, Science, and Transportation; the House Committee on Science, Space, and Technology; and the Director of the Office of Management and Budget. Copies will also be made available to others upon request.

Please contact me on (202) 275-5140 if you or your staff have questions concerning this report. Major contributors to this report are listed in appendix II.

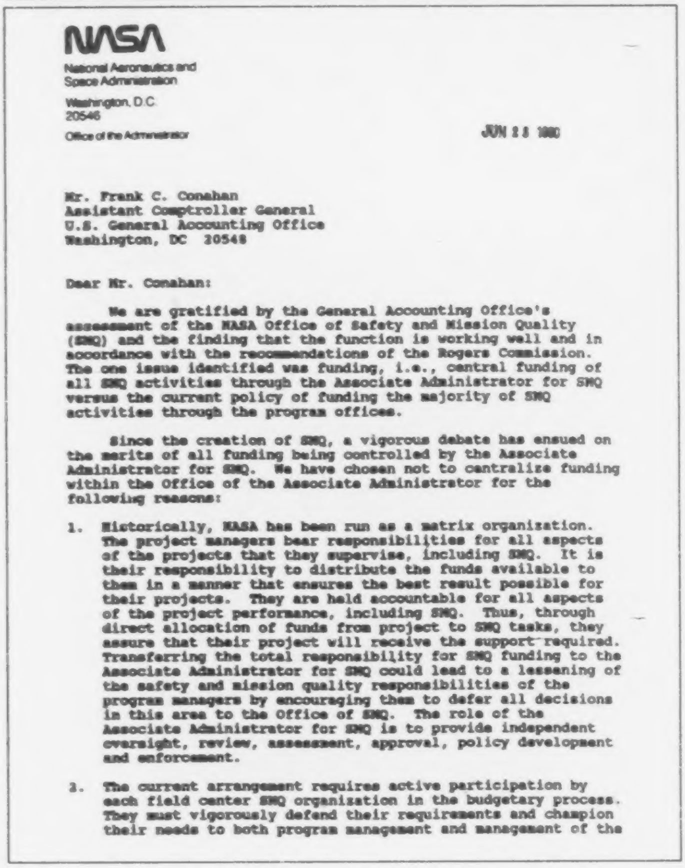
Sincerely yours,

Mark E. Gebicke

Mark E. Gebicke
Director, NASA Issues

Appendix I

Comments From the National Aeronautics and Space Administration



NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

JUN 28 1990

Mr. Frank C. Conahan
Assistant Comptroller General
U.S. General Accounting Office
Washington, DC 20548

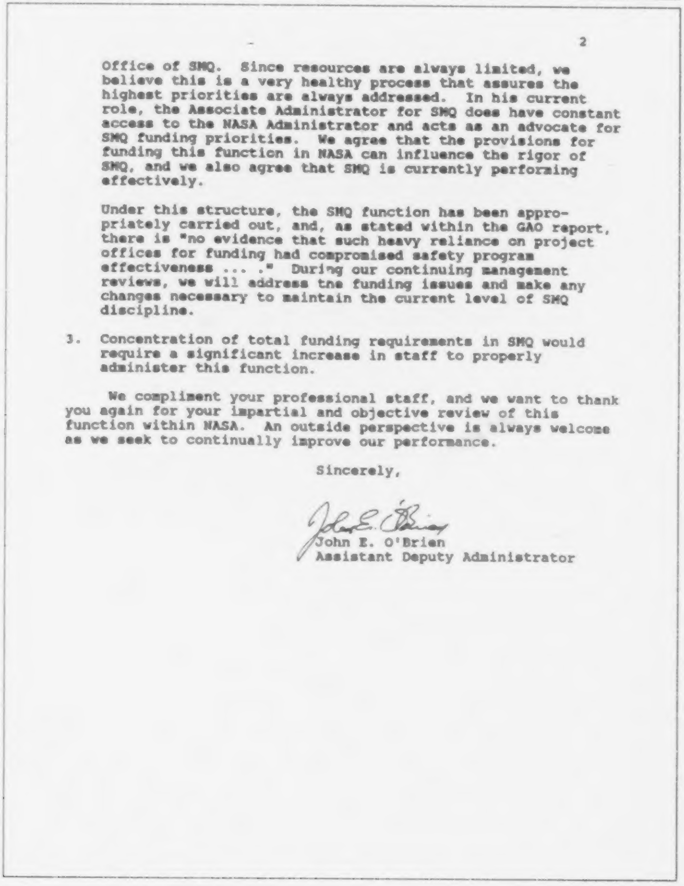
Dear Mr. Conahan:

We are gratified by the General Accounting Office's assessment of the NASA Office of Safety and Mission Quality (SMQ) and the finding that the function is working well and in accordance with the recommendations of the Rogers Commission. The one issue identified was funding, i.e., central funding of all SMQ activities through the Associate Administrator for SMQ versus the current policy of funding the majority of SMQ activities through the program offices.

Since the creation of SMQ, a vigorous debate has ensued on the merits of all funding being controlled by the Associate Administrator for SMQ. We have chosen not to centralize funding within the Office of the Associate Administrator for the following reasons:

1. Historically, NASA has been run as a matrix organization. The project managers bear responsibilities for all aspects of the projects that they supervise, including SMQ. It is their responsibility to distribute the funds available to them in a manner that ensures the best result possible for their projects. They are held accountable for all aspects of the project performance, including SMQ. Thus, through direct allocation of funds from project to SMQ tasks, they assure that their project will receive the support required. Transferring the total responsibility for SMQ funding to the Associate Administrator for SMQ could lead to a lessening of the safety and mission quality responsibilities of the program managers by encouraging them to defer all decisions in this area to the Office of SMQ. The role of the Associate Administrator for SMQ is to provide independent oversight, review, assessment, approval, policy development and enforcement.

2. The current arrangement requires active participation by each field center SMQ organization in the budgetary process. They must vigorously defend their requirements and champion their needs to both program management and management of the



Office of SMQ. Since resources are always limited, we believe this is a very healthy process that assures the highest priorities are always addressed. In his current role, the Associate Administrator for SMQ does have constant access to the NASA Administrator and acts as an advocate for SMQ funding priorities. We agree that the provisions for funding this function in NASA can influence the rigor of SMQ, and we also agree that SMQ is currently performing effectively.

Under this structure, the SMQ function has been appropriately carried out, and, as stated within the GAO report, there is "no evidence that such heavy reliance on project offices for funding had compromised safety program effectiveness ... ." During our continuing management reviews, we will address the funding issues and make any changes necessary to maintain the current level of SMQ discipline.

3. Concentration of total funding requirements in SMQ would require a significant increase in staff to properly administer this function.

We compliment your professional staff, and we want to thank you again for your impartial and objective review of this function within NASA. An outside perspective is always welcome as we seek to continually improve our performance.

Sincerely,

John E. O'Brien

John E. O'Brien
Assistant Deputy Administrator

Appendix II

Major Contributors to This Report

National Security and International Affairs Division, Washington, D.C.	Charles F. Rey, Assistant Director Lawson Gist, Jr., Evaluator-in-Charge Shirley B. Johnson, Evaluator
Atlanta Regional Office	Lee A. Edwards, Regional Management Representative William Stan Lipscomb, Site Senior Willa L. Boutt, Evaluator

United States General Accounting Office

GAO

Report to the Chairman, Committee on
Science, Space and Technology,
House of Representatives

November 1990

SPACE OPERATIONS

NASA Is Not Archiving All Potentially Valuable Data

GAO/IMTEC-91-3

GAO
United States
General Accounting Office
Washington, D.C. 20548

Information Management and
Technology Division

B-240427

November 2, 1990

The Honorable Robert A. Roe
Chairman, Committee on Science, Space,
and Technology
House of Representatives

Dear Mr. Chairman:

On March 2, 1990, we reported on how well the National Aeronautics and Space Administration (NASA) managed, stored, and archived space science data from past missions. This present report, as agreed with your office, discusses other data management issues, including (1) whether NASA is archiving its most valuable data, and (2) the extent to which a mechanism exists for obtaining input from the scientific community on what types of space science data should be archived.

As arranged with your office, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the date of this letter. We will then give copies to appropriate congressional committees, the Administrator of NASA, and other interested parties upon request.

This work was performed under the direction of Samuel W. Bowlin, Director for Defense and Security Information Systems, who can be reached at (202) 275-4649. Other major contributors are listed in appendix IX.

Sincerely yours,

Michael [illegible]

for Ralph V. Carlone
Assistant Comptroller General

Executive Summary

Purpose

The National Aeronautics and Space Administration (NASA) is responsible for space exploration and for managing, archiving, and disseminating space science data. Since 1958, NASA has spent billions on its space science programs and successfully launched over 260 scientific missions. Through these efforts it has collected massive volumes of data for immediate and long-term scientific use stored on over 1.2 million reels of magnetic tape. During the next 5 years NASA plans to launch over 30 new missions, and expects that by the late 1990s the annual volume of its space science data will increase five thousandfold.

Given the nation's investment in space missions, and the need to preserve and safeguard the irreplaceable information they produce, the House Committee on Science, Space, and Technology asked GAO to determine if NASA (1) was archiving all of its valuable space science data, and (2) had a mechanism in place to allow scientists to provide input on what data should be archived.

Background

Space missions generate massive volumes of data. NASA's 1978 policy governing the management of space science data specifies the types of data to be archived. The policy requires missions to archive only data that has been analyzed by principal investigators. The end result of that analysis—archival data—is usually altered and may account for only a small portion of all the data collected. Typically, after analyzed data are archived, tapes containing original and more complete versions of data are erased and reused.

Scientists play a key role in space science research. Scientists that are closely affiliated with specific missions often define mission objectives, analyze spacecraft data, and disseminate the results of their work to the world. Even outside scientists, who are not directly affiliated with specific missions, use spacecraft data—sometimes for research never anticipated when the data were originally collected. Depending on their roles, involvement in the planning, development, and operation of computer systems processing mission data gives affiliated and outside scientists a voice in deciding what mission data should be archived.

Results in Brief

NASA is not archiving all potentially valuable space science data. It does not archive original data from past missions that may be needed for future research. Further, NASA's archives are largely incomplete for many important missions and contain no data for others. Valuable data are missing because (1) NASA's 1978 policy does not require original or certain research and scientific data to be archived, and (2) missions did not prepare requisite plans for data management, archiving, and disposition.

NASA's existing network of committees, advisory panels, and working groups gives scientists an opportunity to provide input on the planning, development, and operation of mission data processing systems. However, affiliated scientists have expressed longstanding concerns that they must be more involved in the actual development and operation of the systems because recommendations they make are often not implemented. Participation of outside scientists is important because they may have different perspectives on the value of data NASA plans to archive. Although NASA policy encourages their participation, it is not required and seldom done. NASA said it was taking steps to expand the role of outside scientists in the management and archiving of space science data.

Principal Findings

Data From Some Important Missions Not Archived

Data from past NASA missions now reside on over 1 million magnetic tapes, yet NASA's existing data archives are incomplete for many important missions and contain no data for others. For 23 out of 37 important scientific missions, less than 60 percent of the required data was archived. And of 263 major science missions NASA launched between 1958-1987, 18 had not sent any data to the archival facility. NASA officials attributed the archival shortfalls to many factors, including a lack of (1) formal agreements between NASA and the principal investigators as to what data to archive, and (2) requirements for archiving of data from certain classes of missions.

Policy Permits the Destruction of Valuable Data

NASA's 1978 data management policy does not require (1) original data to be archived and made available for new research initiatives, or (2) any data to be archived from such sources and disciplines as bioscience, microgravity, aircraft, balloon, sounding rocket missions, and NASA instruments flown on foreign spacecraft or the Shuttle. Many space scientists and NASA advisory groups believe NASA should permanently archive selected original data so that future investigators might have access to original, unmodified data suitable for future processing and analysis. Some scientists feel that where possible, all original data should be saved as a first priority. Although scientists recognize that such a changed policy may require the storage of data in a more voluminous state, they think future scientists must have access to the original, unmodified data for further research and analysis. NASA agrees that its policy needs more flexibility and plans to revise it during 1990.

Mission Archiving Plans Not Prepared

Until recently, NASA had not enforced its own policy that requires missions to prepare project data management plans which address essential aspects of mission data management and archiving. Between May 1978 and October 1985, only one mission prepared the required plan. As a result, these missions have not formally described or identified data that should be archived or marked for destruction.

Scientists' Involvement in a Key Data Management Area Is Ineffective

NASA's Space Science and Applications Advisory Committee, management operations working groups, and mission-level data management and science teams provide a framework through which NASA seeks input from scientists during various mission phases. Mission-level teams often have provisions to involve affiliated and outside scientists in a key data management activity—the planning, development, and operation of mission data processing systems. Although affiliated scientists have been increasingly involved in planning these systems, they still express concern about their limited involvement in the actual development and operation of these systems. As a result, they believe mission data processing systems often do not perform as expected. NASA's efforts to involve outside scientists in data archiving decisions could be strengthened by more actively enlisting outside scientists as members of mission-level advisory committees that guide the development and operation of mission data processing systems, as well as recommend specific data that should be archived for future research.

Recommendations

Although NASA is taking several steps to improve its management of space science data, GAO is making a series of recommendations to the Administrator of NASA to ensure the preservation of all valuable space science data from past and future missions. They include recommendations that NASA (1) take appropriate action to ensure that any valuable missing data from past missions is archived, (2) revise data management policy to ensure that all valuable data are archived, and (3) identify areas where the participation of scientists in data management and archiving activities should be strengthened. Details on these and other recommendations are in chapter 4.

Agency Comments

In commenting on a draft of this report, NASA said that it presents a useful assessment of some key issues in science data management. Further, NASA noted that it shares many of the concerns identified by GAO, and said it has programs underway or plans to address them. NASA's comments and GAO's evaluation are included in appendix IX.

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Abbreviations

CODMAC	Committee on Data Management and Computation
GAO	General Accounting Office
IMTEC	Information Management and Technology Division
ISSPP	Information Systems Strategic Planning Project
JPL	Jet Propulsion Laboratory
NARA	National Archives and Records Administration
NASA	National Aeronautics and Space Administration
NSSDC	National Space Science Data Center
OSSA	Office of Space Science and Applications
PDMP	Project Data Management Plan
SSAAC	Space Science and Applications Advisory Committee
TSSF	Tape Staging and Storage Facility

Chapter 1

Introduction

NASA has spent over $24 billion on space exploration and research during the last three decades. It has launched over 260 major space science missions and acquired massive volumes of data that are stored on more than 1.2 million magnetic tapes, as well as hundreds of thousands of charts, reports, microfilms, negatives, and photographs. Its spectacular successes in many aspects of space exploration have provided scientists with data that have greatly expanded our understanding of the universe, the solar system, and Earth.

Background

NASA's Office of Space Science and Applications (OSSA) is responsible for space exploration and for the overall management, archiving, and dissemination of these data. Individual missions are managed by program managers within OSSA's six science divisions[1] and by mission management teams located at the Goddard Spaceflight Center in Greenbelt, Maryland, the Jet Propulsion Laboratory (JPL) located in Pasadena, California, and other NASA field centers. Responsibility for agency-wide planning, oversight, and coordination of space science data management lies within OSSA's Communications and Information Systems division.

Goddard's National Space Science Data Center (NSSDC) serves as NASA's principal data archival and dissemination facility. In addition, NASA is archiving, or plans to archive, space science data in several discipline data systems[2] and university-based data analysis and archival facilities such as the Infrared Processing and Analysis Center at the California Institute of Technology in Pasadena, the Planetary Data Systems and the NASA Ocean Data System at JPL, and the Pilot Land Data System and the NASA Climate Data System at Goddard.

The National Archives and Records Administration (NARA) is responsible for periodic reviews of NASA's and other federal agencies' management, archiving, and disposal of data. NARA is also responsible for reviewing and approving NASA's records disposition regulations governing the disposal and retention of space science data.

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[1] Life Sciences, Earth Sciences and Applications, Solar System Exploration, Microgravity Science and Applications, Space Physics, and Astrophysics.

[2] Designed to support multiple missions in planetary, space plasma, ocean, land, and climate sciences, these systems archive selected mission data, provide investigators with on-line access to the archived data, and, in some instances, distribute data of high interest on optical disks.

Scientists Play an Important Role in Space Science Research

Space exploration and research is a costly, complex, and often lengthy process requiring close cooperation of hundreds of highly skilled spacecraft and mission planners, designers, engineers, communications specialists, and scientists. Successful space exploration is driven, to a large extent, by scientists who define the mission's scientific focus, analyze the acquired data, and disseminate their findings. In general, scientists who are closely affiliated with NASA missions often serve as principal investigators or co-investigators.[3]

Secondary users of space science data, outside scientists who are not closely affiliated with NASA missions, represent the scientific community at large and substantially contribute to the nation's space exploration and research. Often having served as principal investigators on past missions, they can competently advise NASA on data management and archiving.

Space Missions as Complex Information Systems

The primary objective of NASA space exploration missions is to advance scientific knowledge through data analysis. The first steps in this process are (1) acquiring, (2) processing, and (3) distributing space science data throughout the scientific community. Thus, all major missions include complex information systems consisting of many spaceborne and ground subsystems supported by engineers, data processing specialists, and scientists. These systems may generate and process large volumes and many types of data for periods up to 10 years or more. Given the complexity and volume of data, major missions demand the application of sophisticated inventory, cataloguing, tracking, and data disposition policies and procedures.

Future Missions Pose Significant Data Management Challenges

Future missions will dramatically increase the volume of data that will have to be processed, analyzed, and archived. Between 1990 and 1996, NASA plans to launch over 30 new missions. These missions are expected to produce tremendous volumes of data, unparalleled in NASA's history. NASA estimates that by the late 1990s the annual volume of space science data acquired by its missions will increase five thousandfold.[4] Thus, by the late 1990s, NASA may annually be handling volumes of data about 29 times greater than the volume of text contained in all 15 million books held by the Library of Congress.[5] According to Goddard officials, NASA would annually need over 1.7 million standard reels of magnetic tape or about 48,000 optical disks.

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[3] Appendix II explains in more detail other roles that scientists may have on NASA missions

[4] NASA estimates an increase from .06 terabytes in 1989 to 312 terabytes by the late 1990s

Missions Generate Several Types of Data

In most instances, missions produce large volumes of data which go through several phases from their origination in space to their storage at a NASA archival facility. For ease of understanding, we placed the many types of space science data into two broad categories—original data and archival data.

Original data includes[6] raw data acquired by spacecraft instruments and sensors; master data records that contain the complete original experiment(s) data combined with supporting information such as orbital position, spacecraft attitude, and command and housekeeping data; and experiment data records which are usually extracted from master data records and contain information about a smaller subset of the spacecraft instruments.

Archival data records are usually created and provided to NASA by principal investigators[7] who have analyzed the original data and reported the results of their research through various publications. Often archived data have been irreversibly changed or transformed through calibration and processing, or reduced in volume by sampling. Appendix III shows the general flow of scientific data from spacecraft to data archival facility.

Original Data May Hold Key to Future Research

Original data have greater long-term scientific value that archival data. Archival data records usually contain only a subset of the original data, or calculations based on the original data. Our March 1990 report[8] on NASA's archival practices noted that original data retain their scientific value indefinitely because they (1) are unique and may not be replicated by future missions, (2) may be combined with data from future missions, (3) may be needed to plan future missions, (4) may be needed for long-term studies of environmental changes, (5) may not have been fully analyzed, (6) may be reprocessed using new computer technology and advanced analytical techniques to obtain new or more accurate information, or (7) are of significant historic interest.[9]

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[5] This estimate assumes that an average book contains 300 pages of text, with 400 words per page and 6 characters (bytes) per word. One terabyte is over 1 trillion bytes.

[6] Although original data may include other types—some with no scientific value—we use the term "original" to refer primarily to master data records and experiment data records.

[7] In some instances, archival records may be also created by investigator teams and guest investigators.

[8] Space Operations: NASA Is Not Properly Safeguarding Its Valuable Space Science Data, (GAO/IMTEC-90-1, Mar. 2, 1990).

The Value of Original Data Has Been Established

Many space scientists and NASA advisory groups think that NASA should permanently archive selected original data so that future investigators might have access to original, unmodified data suitable for future processing and analysis. According to NASA's Chief Scientist for the global change research program, scientists need original data from early missions to develop longitudinal data bases. Even if these data have been analyzed before by one group of scientists for one set of purposes, their preservation is increasingly important to scientists in other disciplines.

A group of scientists recognized the long-term value of original data in a 1987 report[10] that focused on ocean data. This report recommended that, where possible, all original data be saved as a first priority before anything else is considered for storage and archiving. While recognizing this would require storing data in their most voluminous state, the report asserted this would allow scientists to reprocess the original, unmodified data sets—an essential condition for further research and analysis. Similarly, a 1989 report of NASA's Information Systems Strategic Planning Project (ISSPP) recommended that all mission data, defined as potentially valuable by the scientific community, must be archived.

The preservation of original data may be important to the global change research program. A 1988 NASA advisory council report[11] identified many data sets generated by past, active, and planned missions as needed for the long term measurements of global variables.

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[9] NASA officials noted that data from some missions may be understood only by the original investigators.

[10] Issues and Recommendations in Satellite Data Management, report of the Satellite Ocean Data System Science Working Group Archive Panel, Scripps Institution of Oceanography, September 1987, p. 5.

[11] Earth System Science: A Close View, Report of the Earth System Science Committee, NASA Advisory Council, NASA, January 1988.

Chapter 2

NASA Is Not Preserving All Valuable Space Science Data

NASA is not preserving all valuable space science data. Except in rare cases, it has not archived original data from past missions that may be needed for future research. Further, NASA's existing data archives are largely incomplete for many important missions and contain no data for others. These conditions can be attributed to a number of factors. NASA is not archiving original data because its 1978 policy covering archiving of space science data is obsolete. The policy requires that only analyzed data be archived. It permits the destruction of original data that may have significant long-term value for future research. Another reason is that until recently, NASA had not enforced its own policy that requires missions to prepare project data management plans (PDMP) which address essential aspects of mission data management and archiving. With one exception, none of NASA's space science missions launched between May 1978 and October 1985 prepared the required plans that should have described and identified data to be archived or marked for destruction.

NASA's management practices do not guarantee that original data from past missions is fully processed, analyzed, and archived by project scientists and principal investigators before being destroyed.

NSSDC officials cited numerous reasons why it had incomplete or missing data for some missions, including (1) no formal agreements between NASA and the principal investigators as to what data to archive, and (2) a policy that did not require the archiving of data from bioscience, microgravity, aircraft, balloon, sounding rocket missions, or data from NASA instruments flown on foreign spacecraft or on the Shuttle. They admitted that management controls covering the destruction of original data could be improved, but could not readily explain why missions did not submit required data plans—other than "until recently, no one in NASA took the PDMP requirement seriously."

No Data Were Archived From Some Important Missions

A number of NASA's past missions have not submitted data to NSSDC. For example, of the 263 major science missions NASA launched between 1958-1987 (see app. IV), 18 had not submitted any data—digital or otherwise—to NSSDC, while 19 had archived only non-digital data such as paper or film records (see app. V).

When asked, NSSDC officials could not readily determine the location and status of data for 28 of the 37 missions. Although unaware of the exact location, they said that it was likely that data for these missions were held by the principal investigators. OSSA officials told us that the program managers in OSSA's science divisions should know where these data are located. Because NASA lacks an agency-wide inventory of its tapes containing space science data, we could not readily verify these statements or determine whether these data were stored elsewhere.

NSSDC officials cited six reasons why the center has not archived any data for these missions. First, there was often no formal agreement between NASA and the principal investigators as to what data to archive. Second, NASA has not previously required the archiving of data from bioscience, microgravity, aircraft, balloon, sounding rocket missions, or NASA instruments flown on foreign spacecraft or the Shuttle. Third, other federal agencies, NASA centers, and universities may be archiving some of these data. Fourth, between 1978-1985, NASA missions did not prepare the required project data management plans identifying data to be archived. Fifth, NSSDC staffing and resources were not, during the last decade, adequate to handle the number, complexity, and volume of data to be archived; thus, missing data may not have been aggressively pursued. NASA recognized this problem in 1988 and is funding NSSDC's data acquisition function at a higher level. Sixth, missions did not accurately estimate the cost of archiving, resulting in insufficient resources to prepare and distribute archival data to NSSDC. In 1989, NSSDC developed a cost model[1] designed to help managers estimate archival costs for their missions. It will also help OSSA's science divisions select the appropriate level of archival service, estimate archival costs, and, one hopes, include adequate funding for archival services in the missions' budgets.

Noting inconsistencies in the kind of data archived from mission to mission or discipline to discipline, a recent report[2] underscored the need to develop a coherent and comprehensive data management policy to preserve all valuable data. Given the absence of uniform format and content requirements for principal investigators to archive their data, it recognized how difficult it is to find archived data and analyze them.

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[1] *A Cost Model for NASA Data Archiving, Version 2.0*, National Space Science Data Center, June 1990.

[2] *Report of the Information Systems Strategic Planning Project: A Recommended Information Systems Strategic Plan for NASA's Office of Space Science and Applications (OSSA) and Office of Space Operations (OSO)*, January 1990, p. 44.

NSSDC's Data Holdings for Many Important Missions Are Incomplete

In 1986, the National Research Council's Committee on Data Management and Computation (CODMAC) requested that NSSDC report on the status of its archival data holdings for 37 missions that CODMAC and NSSDC termed "currently important." NSSDC reviewed its data archives and in June 1987 contacted over 214 principal investigators associated with these missions to locate valuable data that need to be archived. By May 1988, NSSDC received 100 valid and 25 inappropriate responses, with 89 investigators failing to respond to follow-up letters and telephone calls.[3] In a briefing to CODMAC, NSSDC presented a "project report card." Of the 37[4] important missions, only 6 missions had archived more than 90 percent of their data, 7 missions archived between 60 to 90 percent, and 23 missions provided less than 60 percent of data due for archiving at NSSDC. After discussing the ratings with NSEDC staff, we summarized the status of data archival efforts for the 37 missions in Table 2.1.

Table 2.1: Status of Archival Data for Currently Important Missions

Mission (common abbreviation)	Date of launch	Percentage of data archived at NSSDC[a]	Current level of archival effort[b]
1. Atmosphere Explorer C (AE-C)	12/73	60–90	none
2. Atmosphere Explorer D (AE-D)	10/75	60–90	none
3. Atmosphere Explorer E (AE-E)	11/75	60–90	none
4. Active Magnetosphere Particle Tracer Explorer Charge Composition Explorer (AMPTE/CCE)	8/84	60–90	good
5. Active Magnetosphere Particle Tracer Explorer Ion Release Module (AMPTE/IRM)	8/84	> 90	completed[c]
6. Active Magnetosphere Particle Tracer Explorer United Kingdom Subsatellite (AMPTE/UKS)	8/84	0	none[d]
7. Dynamic Explorer 1 (DE-1)	8/81	< 10	very good
8. Dynamic Explorer 2 (DE-2)	8/81	< 10	very good
9. Interplanetary Monitoring Platform J (IMP-J)	10/73	60–90	fair
10. International Sun Earth Explorer 1 (ISEE 1)	10/77	10–29	good
11. International Sun Earth Explorer 2 (ISEE 2)	10/77	10–29	good
12. International Sun Earth Explorer C (ISEE C)	8/78	10–29	good
13. Orbiting Solar Observatory 8 (OSO 8)	6/75	10–29	poor
14. Solar Maximum Mission (SMM)	2/80	30–59	fair

(continued)

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[3] In commenting on the poor response to NSSDC's letter to principal investigators, NSSDC's director noted that if NSSDC could not get information on NASA space science data held by individual investigators, the members of the scientific community may not fare any better.

[4] Data from one mission are archived in England and were therefore not included in our analysis of NSSDC's holdings.

Mission (common abbreviation)		Date of launch	Percentage of data archived at NSSDC[a]	Current level of archival effort[b]
15.	Mariner 6	2/69	< 10	none
16.	Mariner 7	3/69	< 10	none
17.	Mariner 9	5/71	< 10	none
18.	Mariner 10	11/73	30–59	none
19.	Pioneer 10	3/72	30–59	good
20.	Pioneer 11	4/73	30–59	good
21.	Pioneer Venus A Orbiter	5/78	10–29	fair
22.	Pioneer Venus 2	8/78	10–29	fair
23.	Viking 1	8/75	30–59	none
24.	Viking 2	9/75	30–59	none
25.	Voyager 1	9/77	30–59	good
26.	Voyager 2	8/77	30–59	good
27.	High Energy Astronomy Observatory 1 (HEAO 1)	8/77	30–59	very poor
28.	High Energy Astronomy Observatory B (HEAO B)	11/78	60–90	none
29.	High Energy Astronomy Observatory 3 (HEAO 3)	9/79	10–29	very poor
30.	Infrared Astronomical Satellite (IRAS)	1/83	> 90	complete[c]
31.	International Ultraviolet Explorer (IUE)	1/79	> 90	complete[c]
32.	Earth Radiation Budget Satellite (ERBS)	10/84	60–90	good
33.	Heat Capacity Mapping Mission (HCMM)	4/78	100	complete
34.	Nimbus 7	10/78	> 90	complete[c]
35.	Ocean Dynamic Satellite A (SEASAT A)	6/78	30–59	unknown[e]
36.	Solar Mesosphere Explorer (SME)	10/81	> 90	complete
37.	Shuttle Imaging Radar B (SIR-B)	10/84	30–29	unknown[e]

[a] NSSDC estimate of data that should be archived by each mission.

[b] NSSDC's assessment of the level of effort by the principal investigators and projects to generate archival data for submission to NSSDC.

[c] OSSA officials told us that the archiving of data for these missions was successfully completed.

[d] NSSDC officials said that data from this mission are archived in the United Kingdom.

[e] NSSDC was not aware of the current archival efforts because data from this mission are archived at JPL.

An NSSDC official expressed concern about the possible misinterpretation of Table 2.1, since its determination of the volume of data that ought to be archived by the NSSDC is subjective. He provided a listing of facilities storing "as yet not archived" data as well as an explanation of NSSDC's archival effort for these missions. This information is presented in appendix V.

The incompleteness of NSSDC's archives was addressed in a 1989 NASA report which noted that:

> A wealth of data has been acquired on NASA missions and some, but not all, of these data have been submitted to the NSSDC. Scientists involved in NASA programs require access to these data to solve outstanding scientific problems and to prepare for future missions in a situation in which present data are insufficient. These users need to know the extent and quality of the NSSDC data holdings, as does NSSDC, to assess what it has and what it has not, but should have. Thus, NSSDC should perform a complete review of its archive, determine what it needs to curate in its present archive, and what it needs to aggressively procure.[5]

An NSSDC official pointed out that in order to accomplish this objective, NSSDC would need the full cooperation of the scientific community.

Policy Permits the Destruction of Valuable Data

The overall management and archiving of NASA's space science data is governed by a 1978 policy.[6] Among other things, the policy defines the type of space science data records to be archived. It directs NSSDC to archive analyzed data prepared by principal investigators, specifically excludes original data records from permanent archiving, and does not require archiving data from life sciences, microgravity, aircraft, balloon, sounding rocket missions, or from instruments carried by foreign spacecraft and by the Shuttle.[7]

According to NASA officials, OSSA formulated its 1978 policy when most missions were flying instruments that were developed and sometimes built by principal investigators. Because it was believed in nearly all cases that only the principal investigators from these missions could understand and analyze the data, the agency deemed it appropriate to archive only analyzed data identified by the principal investigators as important to save. NASA officials told us they were planning to revise NASA's data management policy during 1990.

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[5] Information Systems Strategic Planning Project, Science User Workshop, Panel Reports, Annapolis, Maryland, May 1-3, 1989, p. 7.

[6] Policy Concerning Data Obtained from Space Flight Investigations, NASA Management Instruction 8030.3A, May 2, 1978.

[7] NASA's sounding rocket and balloon program is managed by Goddard Space Flight Center's Wallops Flight Facility. Wallops launches about 90 balloons and sounding rockets per year. NASA is archiving data from some Shuttle missions, according to one official, "based on common sense rather than on specific rules."

NASA's Records Schedule 26[8] implements portions of the 1978 data management policy and provides day-to-day agencywide guidance on the disposal of space science data. It requires that original data be destroyed after analyzed data have been archived, unless a NASA field center director approves their retention. NASA must seek NARA approval to destroy any unprocessed original data.

Required Mission Data Management Plans Were Not Prepared

Under a key provision of NASA's 1978 data management policy, each mission must prepare a project data management plan. The plans should address all essential functions related to the mission's management and archiving of space science data, including

- plans for data analysis and dissemination,
- milestones for data processing and analysis,
- identification, and time limits for the transfer of valuable data to permanent archives, and
- plans for destroying original data.

NASA stresses the importance of developing this information because the submission of space science data to NSSDC often extends over a period of time much longer than the life of the spacecraft project office, thus making the PDMP a valuable post-project agreement. Because NSSDC is the sole NASA organization responsible for identifying and acquiring archival data in the post-mission phase, its ability to identify and acquire archival data depends on detailed project data management plans and cooperation from each project.

Only one of NASA's 25 space science missions launched between May 1978 and October 1985 prepared the required plans.[9] Hence, these missions, which are listed in appendix VI, have not formally identified data that should be archived or marked for destruction. Since 1988, three out of eight active missions have not prepared the plans. (Appendix VII details the submission of PDMPs for other active and future missions.)

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[8] NASA Records Schedule 26: Computer Sensible—Scientific, Engineering, and Experimental, December 4, 1978.

[9] Although the Infrared Astronomical Satellite does not have a PDMP, the project did prepare an "interface control document" that described data to be archived at NSSDC.

Lax Enforcement Cited as Reason for Noncompliance

Acknowledging the missions' lack of compliance, NASA officials could not explain why NASA has not enforced this requirement. One official responsible for agency-wide coordination of science data management activities noted that until recently, "no one in NASA took the PDMP requirement seriously." The ISSPP task force partially explained the missions' lackluster performance in this area, noting that the development of a data management plan has been imposed on individual projects, but the project has been left to its own devices to prepare this document. No management structure or support approach exists to assist in the implementation of such a plan.[10]

Better Management Safeguards Needed to Prevent Premature Destruction of Original Data

Under NASA's 1978 record disposition policy,[11] tapes containing original data can be released after analyzed data has been archived. We noted, however, that NASA is routinely releasing tapes without adequately ensuring that archival data had been created. Between 1986 to 1989, Goddard released over 532,000 tapes, a large portion of which contained original data.[12]

Current Policies Permit the Disposal of Original Data

NASA's agencywide records management policy permits original data to be destroyed only after analyzed data have been archived. Before destroying any original data that was not analyzed and archived, NASA must obtain approval from NARA. Goddard's local policy, however, does not establish a system of sound management controls to ensure that the required data have been successfully archived before destroying original data. The policy also does not require projects to obtain NARA's approval for destroying data that was not analyzed or archived.

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[10] Information System Strategic Planning (ISSP) Project, Science User Workshop, Annapolis, Maryland, May 1-3, 1989, p. 8.

[11] NASA Records Disposition Handbook (NHB 1441.1A), NASA Records Schedule 26: Computer-sensible—Scientific, Engineering, and Experimental, December 4, 1978; and Goddard Space Flight Center Management Instruction (GMI 8030.1A), Retention of Magnetic Data Tapes, March 7, 1979.

[12] The 532,000 tapes released by Goddard are not included in the count of the 1.2 million tapes in NASA's storage.

No Guarantee at Goddard That Analyzed Data Are Archived Before Original Data Are Destroyed

Original data from many missions are often stored at Goddard. Because of overcrowding at its tape storage facility, as well as the cost of storing magnetic tapes indefinitely, Goddard periodically purges its inventory. Essentially, Goddard gives users two options—release the tapes for reuse, or get special permission from the Director of Goddard and fund their retention. If users elect to release the tapes, they are not specifically required to determine or certify that archival data have been created.

One user explained that he had released thousands of tapes because he could not afford continued storage and was reluctant to raise the retention issue all the way up to the Goddard director. He told us that data on the tapes were valuable, and, in an attempt to salvage some of them, he authorized the destruction of every other carton of tapes, placing the tapes he saved in a basement at Goddard.

Because of concerns about Goddard's practices, we requested NARA to assess Goddard's tape release program and to determine if tapes have been released without proper authorization. On March 27, 1990, NARA representatives met with NASA and Goddard staff to discuss this issue. In a subsequent letter to NASA dated April 6, 1990, NARA noted it could not determine conclusively whether any unauthorized disposal had occurred. According to a NARA official, time constraints and inadequate documentation prevented it from determining whether original data were released without proper authorization. However, because NARA believed that original data may have been destroyed before the archival records were created, it recommended that NASA develop a mechanism to prevent the destruction of original records before analyzed data were archived at NSSDC. A NARA official stated that unless NASA implemented safeguards to protect original data from premature disposal, potentially valuable data may be destroyed.

Chapter 3

Scientists' Participation in Data Management

An extensive network of committees, advisory panels, and working groups exists to involve closely affiliated and outside scientists in data management and archiving decisions and activities. Affiliated scientists are actively involved in broad aspects of planning future missions. However, they have expressed serious concerns about their limited involvement in the development and operation of mission data systems. Outside scientists are generally not involved in data management and archiving activities, even though their involvement is encouraged by NASA policy.

NASA recently sponsored a comprehensive effort known as the Information Systems Strategic Planning Project (ISSPP). The project was formed to develop strategic goals to meet the information systems challenges of the 1990s. It involved nearly 200 participants from the scientific community, NASA headquarters and field centers, and contractors. In general, scientists who were interviewed during the project stated that NASA's mission data systems will never be successful unless they can fully participate in the planning, design, development, operation, and evaluation of these systems. A recent project report[1] noted that scientists' participation on high-level advisory panels was important but not sufficient. The report stated that frequent involvement by scientists on the working level was more essential, allowing them to work closely with NASA centers and contract personnel in developing and operating mission data management systems.

Scientists Participate in Data Management Activities

According to an OSSA official, several mechanisms involve scientists in the management of space science data, including the Space Science and Applications Advisory Committee (SSAAC), management operations working groups, and mission-level data management and science teams.

Scientists Participate in SSAAC and Its Subcommittees to Advise OSSA

In November 1988, NASA established SSAAC to advise OSSA on space observations and the use of space technology in support of space exploration and research. The committee set up several discipline-oriented subcommittees to advise OSSA's science divisions. One of these, the Communications and Information Systems Subcommittee, was specifically chartered to provide advice to OSSA's Communication and Information Systems Division, which is primarily responsible for managing NASA's space science data.

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[1] Information Systems Scenarios for Space Science and Applications, Information Systems Strategic Planning Project, Operations and Information Systems, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, December 1989, p. 6.

SSAAC has met three times since its formation in late 1988. The minutes of its meetings show that the committee and its subcommittees focused largely on funding priorities for proposed missions. It is too early to assess the impact of the new advisory structures on the overall direction of NASA's space exploration research. However, the committee and its subcommittees—particularly the Communication and Information Systems subcommittee—could furnish valuable input and guidance to NASA's management and archiving of space science data.

Scientists Participate in Management Operations Working Groups to Advise OSSA's Science Divisions

OSSA pursues scientist participation on the sub-discipline and project levels through management operations working groups. OSSA officials told us these groups played an important role in allowing scientists not affiliated with NASA missions to participate in the planning and management of various aspects of space science research. In 1989, OSSA's science divisions sponsored 24 groups in the microgravity, space physics, earth science, solar system exploration, flight systems, astronomy and astrophysics, and life sciences disciplines. Although these groups could influence future NASA missions, as well as guide the management and archiving of data collected by past missions, their activities have been largely focused on programmatic, rather than data management, issues.

OSSA is planning to expand the role of outside scientists in the management and archiving of space science data. An OSSA official told us the office has two data management working groups—one ongoing and one planned. The Astrophysics Data System working group operates under the aegis of the Astrophysics division's Science Operations Branch. A second group, the Space Science Data Systems Steering Committee, has been established by the Space Physics division. According to the ISSPP task force, both divisions have gotten user involvement. An NSSDC official also told us that the Life Science discipline has put a group of scientists together, in a committee, to review future data management issues. In addition, the NSSDC is hosting a microgravity data management and archiving workshop.

Mission-Level Teams Making Critical Data Management Decisions Seldom Include Scientists

Project and mission-level teams make detailed data management and archiving decisions. However, scientists, including potential users of data who were not affiliated with a specific mission, seldom participated in mission-level data management and archival decisions. NSSDC guidelines for developing project data management plans stress the importance of establishing mission-level data management advisory committees to guide the development of mission data management and archival plans. Their role is to determine which data should be archived, what ancillary information should be stored with the data, and when and where the archiving should be done. The guidelines recommend that the committee include, if possible, potential investigators–outside scientists—not associated with the mission.

JPL officials who manage the Mars Observer, Galileo, and Magellan missions told us that they were not aware of any NASA guidelines requiring them to seek input from outside scientists. However, they noted that each project published data-related information and seeks input in other forms. Examples they cited included the distribution of project newsletters and consultations with the NASA-funded Planetary Science Data Steering Group. They believed these activities ensured that the interests of the science community were adequately represented.

Scientists Believe Their Participation in a Key Data Management Area Is Ineffective

Despite NASA's efforts to foster scientists' participation in various aspects of space science exploration and research, scientists have expressed concern about their lack of involvement in planning, developing, and operating mission data management systems. This concern is not new. In 1982, CODMAC noted there was commonly a lack of scientific involvement in data-system planning during the early mission planning and system development phase.[2] The committee recommended that NASA involve scientists in all mission phases, noting this involvement should include an oversight of scientific data management activities carried out through a peer review process.

Returning to this problem in 1988, CODMAC reported[3] that NASA emphasized the collection of space science data while paying less attention to its handling, management, and dissemination. The report argued that scientists must help plan data collection activities to ensure high scientific return from the data. The committee recommended that future missions allow scientists to participate more actively in the data management process.

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[2] Data Management and Computation, Volume 1: Issues and Recommendations, Committee on Data Management and Computation, Space Science Board, Assembly of Mathematical and Physical Sciences, National Research Council, National Academy Press, Washington, D.C., 1982, p. 2.

[3] Selected Issues in Space Science Data Management and Computation, Committee on Data Management and Computation, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council, National Academy Press, Washington, D.C., 1988, p. 6.

In December 1989, 7 years after CODMAC's report, NASA's ISSPP repeated the earlier concerns. Its report[4] noted that the number one concern (and frequent complaint) of scientists was the lack of adequate arrangements for user involvement in the planning, design, building, operation, and evaluation of experiment control and information handling systems. Scientists were tired of information systems that did not work well, promises that were never kept, and studies with no follow-through. Underscoring the need for user input on both the advisory and working levels, the report recommended that NASA reverse the recent trend under which the role of university scientists in system planning and development was shrinking in favor of NASA engineers and investigators.

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[4] Information Systems Scenarios for Space Science and Applications, Information Systems Strategic Planning Project, Operations and Information Systems, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, December 1989, p. 5.

Chapter 4

Conclusions and Recommendations

During the last three decades NASA has achieved spectacular success in many aspects of space exploration and has provided scientists with data that have greatly expanded our understanding of the universe, the solar system, and Earth. Through hundreds of missions it has collected massive volumes of data and expects the annual volume to increase five thousandfold by the late 1990s. NASA's data archives, however, are incomplete for many important missions and contain no data for others. For example, 23 of 37 important scientific missions had archived less than 60 percent of the required data, and 18 of the 263 missions launched between 1958 to 1987 sent no data to NSSDC.

NASA officials attributed the archival shortfalls to several factors, including a lack of (1) formal agreements between NASA and the principal investigators as to what data to archive, and (2) requirements to archive data from such sources and disciplines as bioscience, microgravity, aircraft, balloon, sounding rocket missions, and NASA instruments flown on foreign spacecraft or the Shuttle. Considering the onslaught of data expected by the late 1990s, now is a good time to determine if missing archival data from these missions are worth pursuing. If so, NASA should take aggressive steps to obtain outstanding archival data from past missions.

Although many data have been collected over the past 30 years, NASA is not archiving all potentially valuable data. NASA's 1978 data management policy was written when NASA believed that only analyzed data should be saved because scientists may not understand original data. However, analyzed data have often been irreversibly changed or transformed through calibration and processing, or were reduced in volume by sampling. Many space scientists and NASA advisory groups now believe NASA should permanently archive selected original data as a first priority. Although scientists recognize that such a changed policy may require the storage of data in a more voluminous state, they think future scientists must be able to access the original, unmodified data for further research and analysis. NASA agrees that its policy needs more flexibility and plans to revise it during 1990.

NASA's archives are incomplete because it failed for 10 years to enforce its own policy requiring missions to prepare PDMPS, which address essential aspects of mission data management and archiving. With 1 exception, none of NASA's 25 space science missions launched between May

1978 and October 1985[1] prepared them. Because these missions have not formally described or identified data that should be archived or marked for destruction, NSSDC has been hard-pressed to ensure the proper archiving of data from some missions. Recognizing the importance of the plans, NASA now appears headed in the right direction—five of the eight missions launched from February 1988 to July 1990 have submitted the required plans. However, NASA must remain vigilant to ensure that every mission prepares a PDMP well before launch.

NASA must also establish better management controls to ensure that original data are not destroyed until archival data have been provided to the archival facility. Although policy permits original data to be destroyed after analyzed data are archived, it does not require that project offices attest to their creation. We found that NASA had routinely released thousands of tapes—many containing original data—without guaranteeing that analyzed data had been archived. A NARA official echoed our concerns, stating that unless NASA implemented safeguards to protect original data from premature disposal, potentially valuable data may be destroyed.

NASA's extensive network of committees, advisory panels, and working groups provides the basic framework within which scientists can participate in the planning, development, and operation of mission data systems. Groups such as (1) SSAAC and its discipline-oriented subcommittees, (2) the management operations working groups, and (3) mission-level data management and science teams could offer substantial advice and guidance to NASA in all areas of mission planning, development, and operations, if specifically tasked to do so. However, early efforts by several of these groups have apparently focused on budget and programmatic problems, with less attention to data management issues. In addition, groups of scientists have persistently complained about their lack of involvement in the development and operation of mission data management systems. This was cited as a continuing problem by CODMAC in 1982 and 1988, and again by NASA's own ISSPP task force in 1989.

NASA could increase the involvement of scientists in data management and archiving activities by requiring, rather than encouraging, projects to enlist outside scientists as members of the mission-level data management advisory committees. These teams make important decisions on which data should be archived, what additional information should be stored with the data to make it more usable, and when and where the archiving should be done.

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[1] This covers the time period between the date the PDMP requirement went into effect and the last mission launched prior to the Challenger accident.

Recommendations

We recommend that the Administrator:

- require NSSDC to identify and, if warranted and cost effective, obtain all outstanding archival data from past missions not yet delivered to its archives;
- revise data management policy to (1) recognize the need to archive selected original data of potential long-term scientific value, and (2) specify archiving requirements for data produced by life science, microgravity, aircraft, balloon, and sounding rocket missions, and data from NASA instruments flown on Shuttle missions and foreign spacecraft;
- ensure that all missions develop and submit approved PDMPS;
- establish and enforce an internal controls system to ensure that original data are not destroyed until NSSDC has received all appropriate archival data; and
- determine what additional actions could be taken to (1) involve scientists more in the development and operation of mission data management systems, and (2) more strongly encourage missions to include participation of outside scientists on mission-level data management committees.

Agency Comments

In commenting on a draft of this report, NASA said that it presents a useful assessment of some key issues in science data management. Further, NASA noted that it shares many of the concerns we identified, and said it has programs underway or plans to address them. NASA's comments and our evaluation are included in appendix IX.

Objectives, Scope, and Methodology

On November 9, 1988, the House Committee on Science, Space, and Technology asked us to report on several aspects of NASA's management and archiving of space science data. Our first report on this subject was issued on March 2, 1990.[1] Our current objectives were to determine (1) whether NASA is archiving its most valuable data, and (2) the extent to which a mechanism exists for obtaining input from the scientific community on what types of space science data should be archived.

To meet these objectives, we:

- reviewed NASA's policies and guidelines governing the management, archiving, and destruction of space science data;
- reviewed reports and documents related to the management of space science data, including reports prepared by NASA and various scientific groups and committees;
- interviewed NASA and JPL officials responsible for the overall management of NASA's space science data;
- interviewed NSSDC representatives and analyzed NSSDC's archival data holdings;
- interviewed NARA officials responsible for overseeing NASA's record management activities; and
- interviewed JPL project managers and staff responsible for the design, development, and operations of the Galileo mission to Jupiter, Magellan mission to Venus, and the Mars Observer mission.

Our audit work was performed in accordance with generally accepted government auditing standards, between December 1989 and May 1990. We obtained written comments on a draft of this report from NASA officials and have incorporated these comments where appropriate.

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[1] Space Operations: NASA Is Not Properly Safeguarding Valuable Data From Past Missions (GAO/IMTEC-90-1, Mar. 2, 1990).

Appendix II

Scientists' Involvement

Principal Investigators

Virtually all of NASA's past missions and some future missions used or will use the principal investigator model. Under this approach or model, the principal investigators, frequently working with co-investigators, are responsible for the planning, development, and integration of experiments and instruments, data analysis, and the selection and preparation of the analyzed data for archiving.

Guest Investigators

Although guest investigators seldom participate in the initial mission planning or instrument design, they have access to space science data to conduct independent investigations. This approach was used in several missions, and NASA plans to use this approach in future missions, most notably the Hubble Space Telescope, which will have a major guest investigator component.

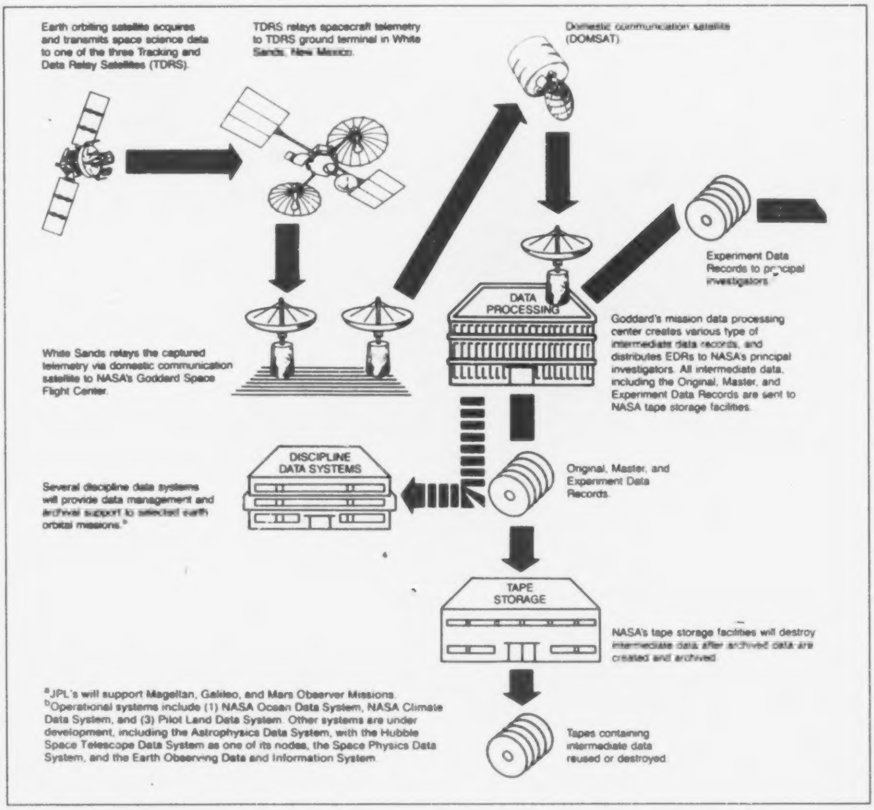
Investigator Team Member

The members of an investigator team usually share data acquired by their instruments. This approach helps collaborative research and allows them to share intermediate results and data processing techniques. For example, this approach worked in the Atmospheric Explorer program, where a common mission data base was accessible to all investigators.

Retrospective Investigator

To a great extent, retrospective investigators represent the scientific community. They are usually not associated with NASA missions and play no part in the instrument development, the initial data analysis, or in archiving analyzed or reduced data. By and large, they conduct research using data archived by the NSSDC or by other NASA data storage facilities and projects, as well as data provided informally by the principal investigators.

Typical Data Flow From Past Earth-Orbiting or Deep Space Missions



Earth orbiting satellite acquires and transmits space science data to one of the three Tracking and Data Relay Satellites (TDRS).

TDRS relays spacecraft telemetry to TDRS ground terminal in White Sands, New Mexico.

Domestic communication satellite (DOMSAT).

White Sands relays the captured telemetry via domestic communication satellite to NASA's Goddard Space Flight Center.

Experiment Data Records to principal investigators.[a]

Goddard's mission data processing center creates various type of intermediate data records, and distributes EDRs to NASA's principal investigators. All intermediate data, including the Original, Master, and Experiment Data Records are sent to NASA tape storage facilities.

Several discipline data systems will provide data management and archival support to selected earth orbital missions.[b]

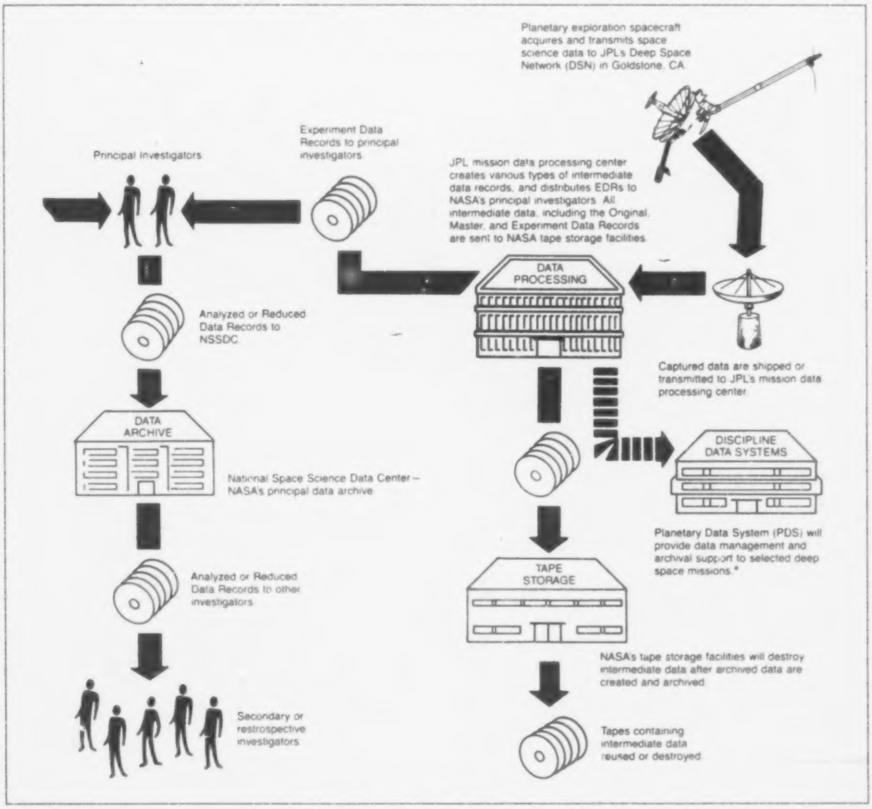
Original, Master, and Experiment Data Records.

NASA's tape storage facilities will destroy intermediate data after archived data are created and archived.

Tapes containing intermediate data reused or destroyed.

[a] JPL's will support Magellan, Galileo, and Mars Observer Missions.

[b] Operational systems include (1) NASA Ocean Data System, NASA Climate Data System, and (3) Pilot Land Data System. Other systems are under development, including the Astrophysics Data System, with the Hubble Space Telescope Data System as one of its nodes, the Space Physics Data System, and the Earth Observing Data and Information System.



Planetary exploration spacecraft acquires and transmits space science data to JPL's Deep Space Network (DSN) in Goldstone, CA

Principal Investigators

Experiment Data Records to principal investigators

JPL mission data processing center creates various types of intermediate data records, and distributes EDRs to NASA's principal investigators. All intermediate data, including the Original, Master, and Experiment Data Records are sent to NASA tape storage facilities.

Analyzed or Reduced Data Records to NSSDC

Captured data are shipped or transmitted to JPL's mission data processing center

National Space Science Data Center – NASA's principal data archive

Planetary Data System (PDS) will provide data management and archival support to selected deep space missions.*

Analyzed or Reduced Data Records to other investigators

NASA's tape storage facilities will destroy intermediate data after archived data are created and archived

Secondary or restrospective investigators

Tapes containing intermediate data reused or destroyed

Appendix IV

Holdings From Major Missions Archived by the NSSDC

			Quantity of holdings by storage medium[a]		
Mission name	**Alternate name(s)**	**Launch date**	**Tapes**	**Paper**	**Film**
Pioneer 1	Able 1	10/11/58	0	4	6
Pioneer 3	1958 THETA 1	12/6/58	0	0	0
Vanguard 2	Vanguard SLV 4	2/17/59	0	0	13
Pioneer 4	1959 NU 1	3/3/59	0	0	0
Explorer 6	Able 6	8/7/59	3	14	109
Vanguard 3	Vanguard TV4 Backup	9/18/59	1	0	11
Explorer 7	1959 Iota 1	10/13/59	18	0	10
Pioneer 5	1960 ALPHA 1	3/11/60	0	2,000	39
TIROS 1	Television Infrared Observation Satellite 1 (TIROS A)	4/1/60	0	0	4
ECHO 1	1960 IOTA 1	8/12/60	1	0	38
Explorer 8	1960 XI 1	11/3/60	0	0	6
TIROS 2	Television Infrared Observation Satellite 2 (TIROS B)	11/23/60	126	0	14
Explorer 9	1960 DELTA 1	2/16/61	0	0	4
P 14	1960 KAPPA 1, Explorer 10	3/25/61	0	0	3
S 15	1960 NU 1, Explorer 11	4/27/61	3	0	7
TIROS 3	Television Infrared Observation Satellite 3 (TIROS C)	7/12/61	79	0	17
EPE-A	1961 UPSILON 1, Explorer 12	8/16/61	37	0	18
S 55A	1961 CHI 1, Explorer 12 (Meteoroid Satellite)	8/25/61	0	0	4
TIROS 4	Television Infrared Observation Satellite 4 (TIROS D)	2/8/62	144	0	22
OSO 1	Orbiting Solar Observatory 1 (OSO A)	3/7/62	27	0	119
ARIEL 1	1962 OMICRON 1, UK 1	4/26/62	2	0	21
TIROS 5	Television Infrared Observation Satellite 5 (TIROS E)	6/19/62	0	0	17
Mariner 2	1962 ALPHA RHO 1	8/27/62	6	0	11
TIROS 6	Television Infrared Observation Satellite 6 (TIROS F)	9/18/62	0	0	23
Alouette 1	1962 BETA ALPHA 1	9/29/62	108	14	10,872
EPE-B	1962 BETA GAMMA 1, Explorer 14	10/2/62	122	0	43
EPE-C	1962 BETA LAMBDA 1, Explorer 15	10/27/62	26	0	9
Relay 1	1962 BETA UPSILON 1	12/13/62	11	3,000	16
S 55B	1962 BETA CHI 1, Explorer 16	12/16/62	0	4	15
AE-A	Atmosphere Explorer A (Explorer 17)	4/3/63	0	0	7
TIROS 7	Television Infrared Observation Satellite 7 (TIROS G)	6/19/63	701	0	52
IMP-A	Interplanetary Monitoring Platform A (IMP 1, Explorer 18)	11/27/63	44	0	20
AD-A	Air Density Explorer A (Explorer 19)	12/19/63	0	0	7
TIROS 8	Television Infrared Observation Satellite 8 (TIROS H)	12/21/63	0	0	29
Relay 2	Relay B	1/21/64	6	0	26
Echo 2	Echo C	1/25/64	1	0	39
Ariel 2	Ariel 2	3/27/64	0	0	14
Ranger 7	RA B	7/28/64	0	0	4,325

(continued)

Mission name	Alternate name(s)	Launch date	Quantity of holdings by storage medium[a]		
			Tapes	Paper	Film
IE-A	Ionosphere Explorer A (Explorer 20)	8/25/64	1	0	1,176
NIMBUS 1	Nimbus A	8/28/64	238	0	195
OGO 1	Orbiting Geophysical Observatory 1 (OGO A)	9/5/64	410	39	146
IMP-B	Interplanetary Monitoring Platform B (IMP 2, Explorer 21)	10/4/64	40	0	11
BE-B	Beacon Explorer B (Explorer 22)	10/10/64	3	27	39
S 55C	Explorer 23	11/6/64	0	1	17
AD-B	Air Density Explorer B (Explorer 24)	11/21/64	0	0	28
Injun 4	Explorer 25	11/21/64	282	0	24
Mariner 4	Mariner 4	11/28/64	12	0	192
San Marco 1	San Marco A	12/15/64	0	0	2
EPE-D	Energetic Particle Explorer D (Explorer 26)	12/21/64	256	0	17
TIROS 9	Television Infrared Observation Satellite 9 (TIROS I)	1/22/65	0	0	18
OSO 2	Orbiting Solar Observatory 2 (OSO B)	2/3/65	0	0	10
Pegasus 1	Pegasus 1	2/16/65	1	0	17
Ranger 8	Ranger 8	2/17/65	0	0	7,142
Ranger 9	Ranger 9	3/21/65	0	0	5,819
BE-C	Beacon Explorer C (Explorer 27)	4/29/65	140	0	55
Pegasus 2	Pegasus 2	5/25/65	1	0	17
IMP-C	Interplanetary Monitoring Platform C (IMP 3 Explorer 28)	5/29/65	118	0	15
Gemini 4	Gemini 4	6/3/65	0	0	0
TIROS 10	Television Infrared Observation Satellite 10	7/2/65	0	0	12
Pegasus 3	Pegasus 3	7/30/65	1	0	16
Gemini 5	Gemini 5	8/21/65	0	0	1
OGO 2	Orbiting Geophysical Observatory 2 (OGO C)	10/14/65	43	227	35
GEOS 1	Geodetic Explorer 1 (GEOS A, Explorer 29)	11/6/65	274	0	7
Pioneer 6	Pioneer A	12/16/65	47	122	39
Solar Explorer	Explorer 30	11/19/65	22	0	13
DME-A	Explorer 31	11/29/65	100	0	2,539
Alouette 2	Alouette B	11/29/65	118	1,626	7,348
Gemini 7	Gemini 7	12/4/65	0	0	1
ESSA 1	OT 3	2/3/66	0	0	10
ESSA 2	OT 2	2/28/66	0	0	22
NIMBUS 2	Nimbus C	5/15/66	1,858	5	3,031
AE-B	Atmosphere Explorer B (Explorer 32)	5/25/66	1	1	9
Surveyor 1	Surveyor 1	5/30/66	0	0	11,540
OGO 3	Orbiting Geophysical Observatory 3 (OGO B)	6/7/66	254	0	782
PAGEOS 1	Pageos A	6/24/66	55	0	24
IMP-D	Interplanetary Monitoring Platform D (AIMP 1)	7/1/66	436	0	60
Gemini 10	Gemini 10	7/18/66	0	0	1

(continued)

Mission name	Alternate name(s)	Launch date	Quantity of holdings by storage medium[a]		
			Tapes	Paper	Film
Lunar Orbiter 1	Lunar Orbiter A	8/10/66	17	0	1,315
Pioneer 7	Pioneer B	8/17/66	28	94	29
Gemini 11	Gemini 11	9/12/66	0	0	0
Lunar Orbiter 2	Lunar Orbiter B	11/6/66	22	0	35,011
Gemini 12	Gemini 12	11/11/66	0	0	0
ATS 1	Application Technology Satellite 1 (ATS B)	12/7/66	142	36	99
Biosatellite 1	Biosatellite 1	12/14/66	0	0	0
ESSA 4	TOS B	1/26/67	0	1	6
Lunar Orbiter 3	Lunar Orbiter C	2/5/67	22	0	20,960
OSO 3	Orbiting Solar Observatory 3 (OSO E)	3/8/67	293	0	24
ATS 2	Application Technology Satellite 2 (ATS A)	4/6/67	65	0	15
Surveyor 3	Surveyor 3	4/17/67	1	0	12,997
ESSA 5	TOS C	4/20/67	0	0	13
San Marco 2	San Marco B	4/26/67	0	0	3
Lunar Orbiter 4	Lunar Orbiter D	5/4/67	18	0	19,281
Ariel 3	UK 3	5/5/67	138	0	70
IMP-F	Interplanetary Monitoring Platform F (IMP 4, Expl. 34)	5/24/67	388	17	521
Mariner 5	Mariner Venus 67	6/14/67	10	0	4
IMP-E	Interplanetary Monitoring Platform E (AIMP 2, Expl. 35)	7/19/67	402	0	170
OGO 4	Orbiting Geophysical Observatory 4 (OGO D)	7/28/67	580	0	219
Lunar Orbiter 5	Lunar Orbiter E	8/1/67	21	0	35,045
Biosatellite 2	Biosatellite 2	9/7/67	0	0	12
Surveyor 5	Surveyor E	9/8/67	4	0	36,487
OSO 4	Orbiting Solar Observatory 4 (OSO D)	10/18/67	29	0	26
ATS 3	Application Technology Satellite 3 (ATS C)	11/5/67	0	5	86
Surveyor 6	Surveyor F	11/7/67	2	0	60,512
ESSA 6	TOS D	11/10/67	0	5	11
Pioneer 8	Pioneer C	12/13/67	19	52	65
TETR 1	Test and Training Satellite 1 (TETR A)	12/13/67	0	0	2
Surveyor 7	Surveyor G	1/7/68	3	0	42,241
GEOS 2	Geodetic Explorer 2 (GEOS B, Explorer 36)	1/11/68	81	0	31
OGO 5	Orbiting Geophysical Observatory 5 (OGO E)	3/4/68	918	0	599
SOLRAD 9	Explorer 37	3/5/68	0	0	0
ESRO 2	International Radiation Satellite 1 (ESRO 2B, IRIS)	5/17/68	0	0	2
RAE-A	Radio Astronomy Explorer A (RAE 1, Explorer 38)	7/4/68	0	0	2,499
AD-C	Air Density Explorer C (Explorer 39)	8/8/68	0	0	18
Injun 5	Injun C (Explorer 40)	8/8/68	11,829	0	21,829
ATS 4	Application Technology Satellite 4 (ATS D)	8/10/68	0	0	2
ESSA 7	TOS E	8/16/68	0	0	7

(continued)

Mission name	Alternate name(s)	Launch date	Quantity of holdings by storage medium[a]		
			Tapes	Paper	Film
Aurora	ESRO 1A	10/3/68	0	0	1
TETR 2	Test and Training Satellite 2 (TETR B)	11/8/68	0	0	14
Pioneer 9	Pioneer D	11/8/68	14	53	37
HEOS 1	HEOS A	12/5/68	12	3	6
OAO 2	Orbiting Astronomical Observatory 2 (OAO A2)	12/7/68	427	0	125
ESSA 8	TOS F	12/15/68	0	0	22
OSO 5	Orbiting Solar Observatory 5 (OSO F)	1/22/69	499	0	731
ISIS 1	ISIS A	1/30/69	150	14	6,274
Mariner 6	Mariner 6	2/25/69	16	0	572
ESSA 9	TOS G	2/26/69	0	0	14
Apollo 9	Apollo 9	3/3/69	0	0	0
Mariner 7	Mariner Mars 69B	3/27/69	21	0	694
NIMBUS 3	Nimbus B2	4/14/69	1,545	12	10,413
OGO 6	Orbiting Geophysical Observatory 6 (OGO F)	6/5/69	516	0	186
IMP-G	Interplanetary Monitoring Platform G (IMP 5, Explorer 41)	6/21/69	648	28	30
Biosatellite 3	Biosatellite D	6/29/69	0	0	2
Apollo 11	Apollo 11	7/16/69	25	1	6,515
PAC-A	Package Attitude Control	8/9/69	0	0	9
OSO 6	Orbiting Solar Observatory 6	8/9/69	84	0	28
ATS 5	Application Technology Satellite 5	8/12/69	320	0	55
Boreas	ESRO 1B	10/1/69	0	0	1
GRS-A	German Research Satellite A (AZUR)	11/8/69	60	0	5
Apollo 12	Apollo 12	11/14/69	1,970	1	21,671
ITOS 1	TIROS M	1/23/70	0	0	4
SERT 2	Space Electric Rocket Test 2	2/4/70	0	0	12
TOPO 1	TOPO 1	4/8/70	0	0	1
NIMBUS 4	Nimbus 4	4/8/70	3,278	0	12,667
Apollo 13	Apollo 13	4/11/70	2	1	2,241
OFO 1	Orbiting Frog Otolith	11/9/70	0	0	0
RMS	Radiation Meteoroid Satellite	11/9/70	0	0	1
NOAA 1	ITOS A	12/11/70	0	0	2
SAS-A	Small Astronomy Satellite A	12/12/70	352	0	15
Apollo 14	Apollo 14	1/31/71	6	1	28,285
IMP-I	Interplanetary Monitoring Platform I (Explorer 43)	3/13/71	286	11	1,881
San Marco 3	San Marco 3	4/24/71	0	0	7
ISIS 2	ISIS 2	4/31/71	273	54	6,028
Mariner 9	Mariner 9	5/30/71	50	86	44,531
SOLRAD 10	Explorer 44	7/8/71	0	0	21
Apollo 15	Apollo 15	7/26/71	2,072	4	80,436

(continued)

			Quantity of holdings by storage medium[a]		
Mission name	**Alternate name(s)**	**Launch date**	**Tapes**	**Paper**	**Film**
Apollo 15 SUBST	Apollo 15 Subsatellite	8/4/71	737	0	74
EOLE 1	CAS A	8/16/71	1	0	4
TETR 4	Test and Training Satellite 4	9/29/71	0	0	2
OSO 7	Orbiting Solar Observatory 7	9/29/71	134	1	193
S-Cubed A	Small Scientific Satellite A (Explorer 45)	11/15/71	25,072	0	1,391
Ariel 4	Ariel 4	12/11/71	1,904	0	6
HEOS 2	HEOS 2	1/31/72	15	0	3
Pioneer 10	Pioneer F	3/3/72	317	5	517
TD 1A	TD 1	3/12/72	3	0	7
Apollo 16	Apollo 16	4/16/72	2,110	1	90,121
Apollo 16 SUBST	Apollo 16 Subsatellite	4/24/72	95	0	8
LANDSAT 1	Earth Resources Technology Satellite A	7/23/72	0	0	20
Explorer 46	Meteoroid Technology Satellite	8/13/72	0	0	6
OAO 3	Orbiting Astronomical Observatory 3 (Copernicus)	8/21/72	50	145	198
IMP-H	Interplanetary Monitoring Platform H (Explorer 47)	9/22/72	886	26	1,559
NOAA 2	ITOS D	10/15/72	0	0	7
SAS-B	Small Astronomy Satellite B (Explorer 48)	11/16/72	1	1	1,743
ESRO 4	ESRO 4	11/21/72	3	0	4
Apollo 17	Apollo 17	12/7/72	8	0	86,242
NIMBUS 5	Nimbus E	12/11/72	3,151	0	47,279
Aeros	Aeros	12/16/72	2	0	18
Pioneer 11	Pioneer G	4/6/73	333	8	791
Skylab	Skylab	5/14/73	1,197	48	41,085
Skylab CSM 1	Skylab Command and Service Module 1	5/25/73	0	0	0
RAE-B	Radio Astronomy Explorer B (Explorer 49)	6/10/73	13	0	82
Skylab CSM 2	Skylab Command and Service Module 2	7/28/73	0	0	1,600
IMP-J	Interplanetary Monitoring Platform J (Explorer 50)	10/25/73	1,677	90	5,556
Mariner 10	Mariner 73	11/3/73	590	1	15,186
NOAA 3	ITOS F	11/6/73	0	0	8
Skylab CSM 3	Skylab Command and Service Module 3	11/16/73	0	0	4,800
AE-C	Atmosphere Explorer C (Explorer 51)	12/16/73	869	0	127
San Marco 4	San Marco C2	2/18/74	0	0	14
SMS 1	Synchronous Meteorological Satellite 1	5/17/74	6,561	0	4,343
ATS 6	Application Technology Satellite 6	5/30/74	1,186	1	1,693
Hawkeye	Injun F (Explorer 52)	6/3/74	0	0	14
Aeros 2	Aeros B	7/16/74	8	0	7
ANS	Astronomical Netherlands Satellite	8/30/74	2	0	8
UK 5	United Kingdom 5	10/15/74	2	0	18

(continued)

Mission name	Alternate name(s)	Launch date	Quantity of holdings by storage medium[a]		
			Tapes	Paper	Film
NOAA 4	ITOS G	11/15/74	0	0	14
Helios-A	Helios 1	12/10/74	177	1	85
LANDSAT 2	Earth Resources Technology Satellite B	1/22/75	0	0	15
SMS 2	Synchronous Meteorological Satellite 2	2/6/75	6,392	0	3,823
GEOS 3	Geodetic Explorer 3	4/9/75	160	0	15
SAS-C	Small Astronomy Satellite C (Explorer 53)	5/7/75	0	24	3,019
NIMBUS 6	Nimbus F	6/12/75	1,058	0	48,538
OSO 8	Orbiting Solar Observatory 8	6/21/75	660	1	213
ASTP-Apollo	Apollo Soyuz Test Project	7/15/75	4	0	3,633
COS-B	Cosmic Ray Satellite B	8/9/75	0	0	0
Viking 1	Viking B	8/20/75	668	7	56,785
Viking 2	Viking A	9/9/75	520	1	37,486
AE-D	Atmosphere Explorer D (Explorer 54)	10/6/75	44	0	3
GOES 1	Geostationary Environmental Satellite A	10/16/75	5,289	0	2,934
AE-E	Atmosphere Explorer E (Explorer 55)	11/20/75	886	0	29
Helios-B	Helios 2	1/15/76	98	1	65
LAGEOS	Laser Geodetic Satellite	5/4/76	115	0	0
NOAA 5	ITOS H	7/29/76	0	0	12
GEOS/ESA	GEOS 1	4/20/77	22	0	14
GOES 2	Geostationary Environmental Satellite B	6/16/77	2,957	0	103
GMS	Geostationary Meteorological Satellite	7/14/77	0	0	1
HEAO 1	High Energy Astronomy Observatory 1 (HEAO A)	8/12/77	186	0	113
Voyager 2	Mariner Jupiter/Saturn B	8/20/77	385	1	68,466
Voyager 1	Mariner Jupiter/Saturn A	9/5/77	409	1	83,660
ISEE 1	International Sun Earth Explorer 1 (ISEE A)	10/22/77	629	2	9,435
ISEE 2	International Sun Earth Explorer 2 (ISEE B)	10/22/77	267	0	2,120
METEOSAT 1	Meteorological Satellite A	11/23/77	0	0	0
IUE	International Ultraviolet Explorer	1/26/78	1,460	0	55,501
LANDSAT 3	Earth Resources Technology Satellite C	3/5/78	0	0	6
HCMM	Heat Capacity Mapping Mission	4/26/78	2,678	0	158,830
Pioneer Venus 1	Pioneer Venus Orbiter	5/20/78	411	4	5,580
GOES 3	Geostationary Environmental Satellite C	6/16/78	619	0	841
SEASAT 1	Ocean Dynamics Satellite A (SEASAT A)	6/26/78	19	0	3
GEOS-B/ESA	GEOS 2	7/14/78	15	0	28
Pioneer Venus 2	Pioneer Venus 78	8/8/78	31	2	8
ISEE 3	International Sun Earth Explorer 3 (ISEE C)	8/12/78	181	0	6,685
CAMEO	Chemically Active Materials Ejected in Orbit	10/24/78	0	0	0
TIROS-N	Television Infrared Observation Satellite N	10/13/78	1	0	3
NIMBUS 7	Nimbus G	10/24/78	13,595	0	88,796

(continued)

Appendix IV
Holdings From Major Missions Archived by the NSSDC

Mission name	Alternate name(s)	Launch date	Quantity of holdings by storage medium[a]		
			Tapes	Paper	Film
HEAO 2	High Energy Astronomy Observatory 2 (HEAO B, Einstein)	11/13/78	23	0	22
SAGE	Stratospheric Aerosol and Gas Experiment (AEM B)	2/18/79	235	0	2
UK 6	Ariel 6	6/2/79	0	1	3
NOAA 6	NOAA A	6/27/79	0	0	0
HEAO 3	High Energy Astronomy Observatory 3 (HEAO C)	9/20/79	33	0	1
MAGSAT	Global Magnetic Survey Mission (AEM C)	10/30/79	228	0	65
SMM	Solar Maximum Mission	2/14/80	7	0	232
GOES 4	Geostationary Environmental Satellite D	9/9/80	0	0	0
GOES 5	Geostationary Environmental Satellite E	5/22/81	17	0	0
DE 2	Dynamics Explorer 2 (DE B)	8/3/81	4	0	41
DE 1	Dynamics Explorer 1 (DE A)	8/3/81	8	0	50
SME	Solar Mesosphere Explorer	10/6/81	131	0	0
STS 2/OSTA-1	Office of Space and Terrestrial Application 1	11/12/81	11	0	2,200
STS 3/OSS-1	Shuttle OFT 3	3/22/82	0	0	2,582
IRAS	Infrared Astronomical Satellite	1/25/83	165	0	1,178
NOAA 8	NOAA E	3/28/83	0	0	0
GOES 6	Geostationary Environmental Satellite F	4/28/83	81	0	0
EXOSAT	European X-Ray Observatory Satellite	5/26/83	1	0	0
Spacelab 1	Spacelab 1 (STS-9)	11/28/83	0	0	0
AMPTE/CCE[b]	Active Magnetospheric Particle Tracer Explorer	8/16/84	78	0	63,597
AMPTE/IRM	AMPTE/Ion Release Module	8/16/84	194	0	4
AMPTE/UKS	AMPTE/United Kingdom Subsatellite	8/16/84	0	0	1
ERBS	Earth Radiation Budget Satellite	10/5/84	277	5	0
STS-41G	Shuttle Imaging Radar B (SIR B)	10/5/84	173	0	36,298
NOAA 9	NOAA F	12/12/84	120	2	0
Spacelab 3	STS-51B	4/29/85	23	0	0
PDP	Plasma Diagnostic Package	7/29/85	0	0	0
Spacelab 2	STS-51F	7/29/85	13	50	2,924
Spacelab D-1	STS-61A	10/30/85	0	0	0
NOAA 10	NOAA G	9/17/86	0	0	0
GOES 7	Geostationary Environmental Satellite H	2/26/87	0	0	0

[a] The numbers in these columns represent identifiable record holdings on three storage media—tape, paper, and film. Units for tape and paper usually represent individual magnetic tapes or paper documents. Film units may be different, depending on the type of film used. For example, missions using 100-ft reels of microfilm are measured in number of reels. Those using other types of strip film, of various widths, are measured in linear feet of film. Slides or other individually held film frames, are measured in number of slides or frames. Microfiche are measured in number of microfiche cards. The holdings shown do not include ERBS and NOAA 9 data stored on 19 optical disks.

[b] Charge Composition Explorer.

NASA Missions With No Data Archived by the NSSDC

Table V.1: Missions Without Any Data

Mission	Launch date	Possible location of any data[a]
Apollo 9	3/3/69	Unknown
Application Technology Satellite 4 (ATS 4)	8/10/68	Unknown
Biosatellite 1	12/14/66	University of New Mexico
Biosatellite 2	9/7/67	Unknown
Biosatellite 3	6/29/69	Unknown
Gemini 4	6/3/65	EROS Data Center
Gemini 11	9/12/66	EROS Data Center
Gemini 12	11/11/66	EROS Data Center
Hawkeye	6/3/74	University of Iowa
Orbiting Frog Otolith 1 (OFO 1)	11/9/70	Unknown
Plasma Diagnostic Package (PDP)	7/29/85	University of Iowa
Pioneer 4	3/3/59	Unknown
Pioneer 3	12/6/58	Unknown
Skylab Command and Service Module 1 (CSM 1)	5/25/73	Unknown
Skylab Command and Service Module 2 (CSM 2)	7/28/73	Unknown
Skylab Command and Service Module 3 (CSM 3)	11/16/73	Unknown
Space Transportation Systems 9/Spacelab 1	11/28/83	Unknown
Space Transportation System 61A/Spacelab D-1	10/30/85	Unknown

[a] According to an NSSDC official, for locations showing "unknown", it is likely that these data are being held by the principal investigator or co-investigator. However, NSSDC is unaware of the exact location of these data.

Table V.2: Missions Without Digital Data

Mission	Launch date	Storage media		Possible location of digital data
		Paper	Film	
Air Density Explorer A (AD-A)	12/19/63	0	7	Unknown
Air Density Explorer B (AD-B)	11/21/64	0	28	Unknown
Air Density Explorer C (AD-C)	8/8/68	0	18	Unknown
Atmosphere Explorer A (AE-A)	4/3/63	0	7	Unknown
Application Technology Satellite 3 (ATS 3)	11/5/67	5	86	Unknown
Explorer 9	2/16/61	0	4	Unknown
Explorer 8	11/3/60	0	6	Unknown
Gemini 10	7/18/66	0	1	EROS Data Center
Gemini 7	12/4/65	0	1	EROS Data Center
Gemini 5	8/21/65	0	1	EROS Data Center
ITOS 1	1/23/70	0	4	NOAA
Orbiting Solar Observatory 2 (OSO 2)	2/3/65	0	10	Unknown
Explorer 10	3/25/61	0	3	Unknown
Pioneer 1	10/11/58	0	6	Unknown
Pioneer 5	3/11/60	2,000	39	Unknown
Radio Astronomy Explorer A (RAE-A)	7/4/68	0	2,499	Unknown
Small Astronomy Satellite C (SAS-C)	5/7/75	24	3,019	Unknown
Space Transportation System 3/Office of Space Science 1 (STS-3/OSS-1)	3/22/82	0	2,582	Unknown
Surveyor 1	5/30/66	0	11,540	Unknown

Appendix VI

Location and Status of Data for Currently Important Missions

Atmospheric Explorers (AE)—higher resolution data held by principal investigators.

Active Magnetospheric Particle Tracer Explorers (AMPTE)—some AMPTE/Charge Composition Explorer (CCE) higher resolution data held by AMPTE Science Data Center at John Hopkins University. OSSA and NSSDC officials told us that although CODMAC has identified AMPTE/Ion Release Module (IRM) and AMPTE United Kingdom Subsatellite (UKS) as "currently important scientific missions," NASA and NSSDC are not responsible for archiving data from these missions. However, NSSDC is archiving many AMPTE/IRM data.

Dynamic Explorers (DE)—most data held by principal investigators, being processed before submission to NSSDC.

Interplanetary Monitoring Platform (IMP)—limited unique IMP data held by principal investigators, key data in processing for submission to NSSDC.

International Sun Earth Explorers (ISEE)—most data held by principal investigators, being processed for submission to NSSDC.

Orbiting Solar Observatory (OSO)—all data held by principal investigators.

Solar Maximum Mission (SMM)—most data at Goddard's SMM Data Analysis Center (DAC) for public access; other data readied for submission to DAC; copies of SMM/DAC data will be archived by the NSSDC.

Mariner—data held by principal investigators, some data at JPL.

Pioneer—data held by principal investigators; NASA's Ames Research Center is working with investigators on data archival plans.

Pioneer Venus—data held by principal investigators; NASA's Ames Space Center is working with investigators on data archival plans.

Viking—data held by principal investigators, some data at JPL. Infrared data copied on CD-ROM optical disks (Compact Disk Read Only Memory).

Voyager—data held by principal investigators, JPL's Planetary Data System. Most imaging data on CD-ROMs.

High Energy Astronomy Observatory (HEAO)—most data from HEAO 1 and 3 held by principal investigators. Most data from HEAO B held by the Smithsonian Astronomical Observatory.

Infrared Astronomical Satellite (IRAS)—most data at NSSDC. According to the Infrared Processing and Analysis Center (IPAC) officials, the full set of IRAS data—including original and archival data, is also stored at IPAC at the California Institute of Technology in Pasadena, California, in the Netherlands at University of Groningen and Sterrewach Huygens Laboratorium at the University of Leiden, and in the United Kingdom by the IRAS Post Mission Analysis Facility at Rutherford Appleton Laboratory.

International Ultraviolet Explorer (IUE)—most data at NSSDC.

Earth Radiation Budget Satellite (ERBS)—most data at Langley Research Center; data are routinely submitted to NSSDC archive.

Heat Capacity Mapping Mission (HCMM)—all digitized data at NSSDC. Many raw data still unprocessed.

Nimbus-7—most data at NSSDC, selected data held by Goddard for distribution to investigators in coordination with NSSDC.

Seasat—all data at JPL.

Solar Mesosphere Explorer (SME)—most data at NSSDC, balance held by the University of Colorado.

Shuttle Imaging Radar B (SIR-B)—in compliance with NASA instructions, NSSDC is not distributing SIR-B data to users. In a form letter to scientists requesting SIR-B data, NSSDC notes that in compliance with the congressional decision after a reassessment of the Land Remote Sensing Commercialization Act of 1984, "SIR-B data will be distributed by a private firm yet to be identified."

Appendix VII

NASA Missions Without Project Data Management Plans, 1978-85

Mission name	**Date of launch**
Pioneer Venus Orbiter	5/20/78
Ocean Dynamics Satellite A (SEASAT 1)	6/26/78
Pioneer Venus 78	8/8/78
International Sun Earth Explorer 3 (ISEE 3)	8/12/78
Chemically Active Materials Ejected in Orbit (CAMEO)	10/24/78
Nimbus 7	10/24/78
High Energy Astronomy Observatory (HEAO 2)	11/13/78
Stratospheric Aerosol and Gas Experiment (SAGE)	2/18/79
High Energy Astronomy Observatory (HEAO 3)	9/20/79
Global Magnetic Survey Mission (MAGSAT)	10/30/79
Solar Maximum Mission (SMM)	2/14/80
Dynamics Explorer 1 (DE 1)	8/3/81
Dynamics Explorer 2 (DE 2)	8/3/81
Solar Mesosphere Explorer (SME)	10/6/81
Office of Space and Terrestrial Application (STS 2)	11/12/81
Shuttle OFT 3 (STS3/OSS-1)	3/22/82
Infrared Astronomical Satellite (IRAS)[a]	1/25/83
Spacelab 1	11/28/83
Active Magnetospheric Particle Tracer Explorer (AMPTE/CCE)	8/16/84
Earth Radiation Budget Satellite (ERBS)	10/5/84
Shuttle Imaging Radar B (SIR-B)	10/5/84
Spacelab 3	4/29/85
Plasma Diagnostic Package (PDP)	7/29/85
Spacelab 2	7/29/85
Spacelab D-1	10/30/85

[a] The IRAS mission prepared, in lieu of an PDMP, an agreement for archiving its data at the NSSDC.

Status of Project Data Management Plans for Active and Planned Missions, 1988-91

Missions	Actual Planned Launch	Data PDMP approved
Operational		
San Marco-D	3/1988	2/1988
Magellan	4/1989	5/1989
Galileo	10/1989	3/1990
Shuttle Solar Backscatter Ultraviolet Instrument 1 (SBUV-1)	10/1989	———[c]
Cosmic Background Explorer (COBE)	11/1989	6/1988
Hubble Space Telescope (HST)	4/1990	7/1982
Roentgen Satellite (ROSAT)	6/1990	———[d]
Combined Release and Radiation Effect Satellite (CRRES)	7/1990	———[e]
Planned		
Astronomy Laboratory 1/Broad Band X-Ray Telescope (Astro-1/BBXRT)	1990	2/1990
Space Life Sciences-1 (SLS-1)	1990	———
Ulysses	1990	———
Gamma Ray Observatory (GRO)	1990	———
Shuttle Solar Backscatter Ultraviolet Instrument 2 (SBUV-2)	1990	———
International Microgravity Laboratory 1 (IML-1)	1990	———
Atmospheric Laboratory for Applications and Science 1 (ATLAS-1)	1991	———
Spacelab-J	1991	———
Extreme Ultraviolet Explorer (EUVE)	1991	———
Upper Atmosphere Research satellite (UARS)	1991	———
Laser Geodynamics Satellite II (LAGEOS II)	1991	———

[a] Includes joint missions with foreign governments

[b] Goddard News, Mixed Fleet Manifest, Vol. 36, No 3, March 1990

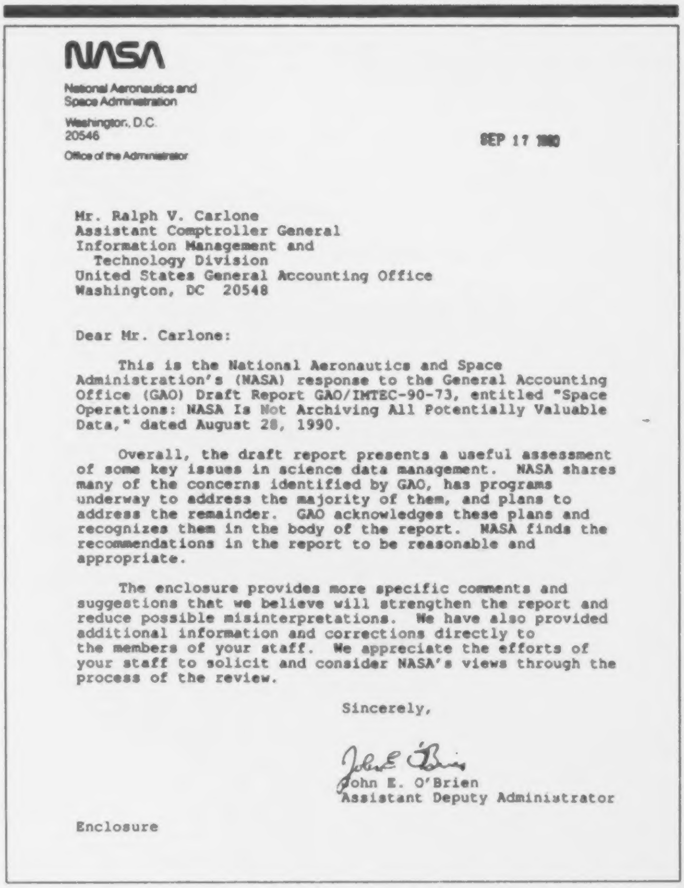
[c] OSSA has no plans to prepare an PDMP for the SSBUV

[d] ROSAT's PDMP is in the signature cycle. This German mission, with NASA instruments, will not be generating data for NASA until March 1991

[e] Data from this mission will largely consist of photographs

Comments From the National Aeronautics and Space Administration

Note: GAO comments supplementing those in the report text appear at the end of this appendix.



NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546
Office of the Administrator

SEP 17 1990

Mr. Ralph V. Carlone
Assistant Comptroller General
Information Management and
  Technology Division
United States General Accounting Office
Washington, DC 20548

Dear Mr. Carlone:

This is the National Aeronautics and Space Administration's (NASA) response to the General Accounting Office (GAO) Draft Report GAO/IMTEC-90-73, entitled "Space Operations: NASA Is Not Archiving All Potentially Valuable Data," dated August 28, 1990.

Overall, the draft report presents a useful assessment of some key issues in science data management. NASA shares many of the concerns identified by GAO, has programs underway to address the majority of them, and plans to address the remainder. GAO acknowledges these plans and recognizes them in the body of the report. NASA finds the recommendations in the report to be reasonable and appropriate.

The enclosure provides more specific comments and suggestions that we believe will strengthen the report and reduce possible misinterpretations. We have also provided additional information and corrections directly to the members of your staff. We appreciate the efforts of your staff to solicit and consider NASA's views through the process of the review.

Sincerely,

John E. O'Brien
Assistant Deputy Administrator

Enclosure

NASA Response To GAO Draft Report

GAO/IMTEC-90-73

I. Executive Summary

NASA agrees in general with the conclusions and recommendations, but does, however, have some concern with respect to the perspective or emphasis that is presented. For instance, the emphasis on having no data archived for 18 of the 263 major science missions launched between 1958-1987 neglects the fact that data is archived for 245 or 93% of the missions.

Another concern is the potentially misleading title chosen to highlight the principal finding concerning scientist involvement in data archiving. "Lack of Scientists' Involvement in a Key Data Management Area" is not a completely accurate assessment. As stated, it is not consistent with the narrative supporting the assertion, nor with the facts and conclusions presented in the body of the report.

Significant parts of the science user community are, in fact, vitally concerned with, and playing key roles in archiving and data management systems. In addition to the investigator working groups that play a key role in flight mission planning, steering groups have been established by the various science discipline offices to oversee and provide advice and guidance in all aspects of data management across the respective discipline programs and projects. Examples include the Planetary Science Data Steering Committee, the Science Operations Working Group for Astrophysics, the Space Physics Data Systems Steering Committee, and the Life Sciences Data Systems Steering Committee. All groups include participants from the outside research community.

While there is no standing committee for Microgravity Science and Applications, a data management workshop involving members of the research community was conducted in July, 1990 and follow-on plans are being developed for an appropriate data management approach.

Furthermore, the Science Advisory Panel for the Earth Observing System Data and Information System (EOSDIS) includes representatives from the broad spectrum of Earth science users; they have been very active in EOSDIS planning to date, and will continue their active role during the course of the program.

NASA recognizes user involvement as a vital element for success; we will continue to build on past experience to strengthen that involvement in all elements of data management. With the context altered above, we certainly agree with the recommendation to continue to do so. We also accept the other recommendations which we consider to be constructive and appropriate.

See comment 1.

II. Chapter 2 "NASA Is Not Preserving All Valuable Space Science Data"

1. In spite of the clarifications provided through footnotes to Table 2.1 on page 18 the table is still potentially misleading. The rightmost column is especially confusing with respect to terminology, perspective, and intended message. For example, Viking, which is presented as having no archival effort, has an active project to restore data under the auspices of the Planetary Data System.

2. The statement on page 22, paragraph 2, "Between 1986 to 1989, Goddard released 532,000 tapes, a large portion of which contained original data", needs to be clarified to avoid misinterpretation. The statement is partially correct, but care should be taken to not surmise that almost half of the 1.2 million data tapes containing all of NASA's science data from 260 missions (described on page 1 of the document) were "released."

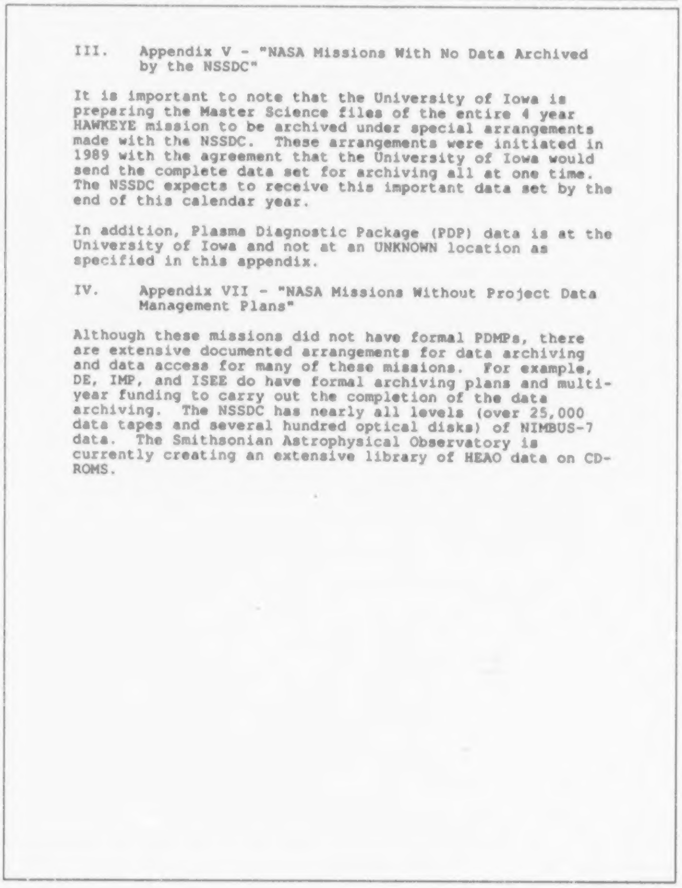
In fact, 532,000 tapes were sent to the Information Processing Division's (IPD) Magnetic Tape Certification Facility for degaussing, cleaning, and recertification for reuse. However, these were comprised of a variety of production-oriented tapes, many of which would never be considered for either short-term retention or long-term archiving.

Another 100,000 of these tapes were from missions such as Nimbus-7 and the Dynamics Explorers, which converted their Level 0 (raw) data to optical disks before releasing their data tapes for recertification.

Many of the other tapes released are from various processing steps in the IPD data processing cycle, including data capture tapes, pre-edit tapes, edit tapes, etc., all of which contain raw data. However, the science community associated with these missions received the required Level 0 products (e.g., decommutated data tapes).

The point is that of the 532,000 tapes that were released, only a small portion were for user data tapes and no tape was degaussed without the user's written permission.

See comment 2



III. Appendix V - "NASA Missions With No Data Archived by the NSSDC"

It is important to note that the University of Iowa is preparing the Master Science files of the entire 4 year HAWKEYE mission to be archived under special arrangements made with the NSSDC. These arrangements were initiated in 1989 with the agreement that the University of Iowa would send the complete data set for archiving all at one time. The NSSDC expects to receive this important data set by the end of this calendar year.

See comment 3.

In addition, Plasma Diagnostic Package (PDP) data is at the University of Iowa and not at an UNKNOWN location as specified in this appendix.

IV. Appendix VII - "NASA Missions Without Project Data Management Plans"

Although these missions did not have formal PDMPs, there are extensive documented arrangements for data archiving and data access for many of these missions. For example, DE, IMP, and ISEE do have formal archiving plans and multi-year funding to carry out the completion of the data archiving. The NSSDC has nearly all levels (over 25,000 data tapes and several hundred optical disks) of NIMBUS-7 data. The Smithsonian Astrophysical Observatory is currently creating an extensive library of HEAO data on CD-ROMS.

See comment 4.

The following are GAO's comments on the National Aeronautics and Space Administration letter dated September 17, 1990.

GAO Comments

1. "Executive Summary"

NASA agrees in general with the report's conclusions and recommendations, but mentions concern about our emphasis on its having no archival data for 18 of the 263 missions launched between 1958-87, believing it neglects the fact that data for 245, or 93 percent of these missions are archived. We acknowledge that some data are archived for most of NASA's missions and worded the executive summary accordingly. However, we consider the total absence of data for 18 missions as a major loss.

NASA also believes that the title we chose to highlight the scientists' involvement in a key data management area is potentially misleading. We modified the title to more accurately reflect our finding.

2. "NASA Is Not Preserving All Valuable Space Science Data"

NASA comments that table 2.1, which shows the status of archival data for currently important missions, is potentially misleading, and in the case of the Viking mission, inaccurate. The information presented in the far right column (which shows the current level of archival effort) was verified by NSSDC, and we believe it to be accurate. NSSDC has also provided more information clarifying the status of archival activities presented in appendix VI.

NASA says that our statement on the release (destruction or reuse) of 532,000 tape should be clarified to show that these tapes are not included in the 1.2 million data tapes kept in data storage facilities. We have clarified our statement in a footnote explaining that the 532,000 tapes are not part of the 1.2 million tapes in NASA's storage facilities.

According to NASA, (1) only a small portion of the 532,000 tapes released by TSSF contained original space science data, and (2) no tapes were released without the user's written permission. We disagree. Even if we exclude the 100,000 tapes from the Nimbus-7 and the Dynamics Explorer missions and an additional 180,000 tapes containing intermediate data not identified with a specific mission, between 1986-89 Goddard released over 200,000 tapes containing original data.

Further, the TSSF tape inventory data base does not provide enough information on the type of data. Second, there is a discrepancy in Goddard's tape release statistics. According to Goddard's initial estimates, between 1986-89 NASA released over 590,000 tapes. However, in June 1990, in response to our request to identify these tapes by spacecraft and type of data, Goddard's estimate of tapes released during this period was 67,000 less than the initial count. Regardless of the exact number of tapes involved, we believe Goddard released at least 200,000 tapes containing original data, and these tapes were released without ensuring that NSSDC had archived the analyzed data.

NASA states that no tape was released without the user's written permission. While we agree that TSSF obtained the signatures of Goddard officials responsible for these tapes, this does not ensure that these data were analyzed and archived at NSSDC.

3. "NASA Missions With No Data Archived by the NSSDC"

NASA pointed out that the University of Iowa is archiving data from the Hawkeye mission and from the Plasma Diagnostic package instruments. We modified appendix V to reflect these efforts.

4. "NASA Missions Without Project Data Management Plans"

NASA comments that while many pre-1985 missions did not prepare formal PDMPs, several had extensive documented arrangements for data archiving and access. We are aware that each NASA mission prepares voluminous reports and plans for the acquisition, processing, analysis, and distribution of mission data. However, we reaffirm our conviction that the lack of formal PDMPs is one reason why data from many missions were not archived. Without the PDMP, there is no single mission document that outlines plans for data analysis, dissemination, archiving, and the destruction of original data.

Appendix X

Major Contributors to This Report

Information Management and Technology Division, Washington, D.C.

Ronald W. Beers, Assistant Director
Mirko J. Dolak, Evaluator-in-Charge
David T. Schwartz, Evaluator
Kurt A. Burgeson, Evaluator
Dennis L. O'Connor, Reports Analyst

Los Angeles Regional Office

Allan Roberts, Regional Assignment Manager
Jeffrey N. Webster, Evaluator

United States General Accounting Office

GAO

Report to Congressional Requesters

January 1990

NASA PROJECT STATUS REPORTS

Congressional Requirements Can Be Met, but Reliability Must Be Ensured

GAO/NSIAD-90-40

GAO

United States
General Accounting Office
Washington, D.C. 20548

National Security and
International Affairs Division

B-237602

January 23, 1990

Congressional Requesters

This report responds to your requests concerning how NASA can routinely produce Project Status Reports that meet your needs for reliable cost, schedule, and performance information on major NASA projects.

We are also distributing copies of this report to the NASA Administrator; the Director, Office of Management and Budget; and other interested parties.

Please contact me at (202) 275-5140 if you or your staff have any questions concerning the report. Other GAO staff members who made major contributions to this report are listed in appendix IV.

Mark E. Gebicke

Mark E. Gebicke
Director, NASA Issues

List of Requesters

The Honorable Albert Gore, Jr., Chairman
Subcommittee on Science, Technology and Space
Committee on Commerce, Science and Transportation
United States Senate

The Honorable Barbara A. Mikulski, Chair
Subcommittee on VA, HUD and Independent Agencies
Committee on Appropriations
United States Senate

The Honorable Robert A. Roe, Chairman
Committee on Science, Space and Technology
House of Representatives

The Honorable Bob Traxler, Chairman
Subcommittee on VA, HUD and Independent Agencies
Committee on Appropriations
House of Representatives

Executive Summary

Purpose

Funding requirements for the National Aeronautics and Space Administration (NASA) are expected to rise dramatically in the 1990s and could triple by the year 2000 if some recently proposed initiatives such as a lunar outpost or a staffed Mars expedition are adopted. Contributing substantially to these prospective increases are major existing and planned research and development projects. The current federal budget deficit environment adds to the challenge facing congressional decisionmakers in making increasingly difficult choices about what civil space projects will be undertaken and the pace at which they will be funded. Reliable information on the cost and progress of NASA's major projects can be a valuable resource for legislators when making budget allocation decisions.

NASA's four principal oversight Committees requested GAO to assess NASA's ability to produce status reports that meet their requirements for reliable cost, schedule, and performance information on major NASA projects. As part of this request, GAO helped the Committees and NASA agree upon project status reporting criteria and reviewed NASA's current process for developing these reports in a reliable manner.

Background

In its report on NASA Issues (GAO/OCG-89-15TR, Nov. 1988), GAO identified NASA's incomplete project cost reporting as an issue to be considered by the incoming administration and the Congress. While developing that report, GAO found that NASA had the capability to report more complete project costs and, on occasion, had done so since the mid-1970s at the request of one of its oversight Committees. In these Project Status Reports, NASA had provided the Committee with cost, schedule, and performance information on selected major projects.

The Project Status Report NASA has prepared since the mid-1970s was patterned after the Department of Defense's Selected Acquisition Reports. The Subcommittee on Veterans Affairs, Housing and Urban Development and Independent Agencies, Senate Committee on Appropriations, specified the NASA projects to be reported. From 1976 through 1989, NASA prepared 146 reports on 17 different projects. Project Status Reports were initially submitted on January 30 and July 31 of each year. However, since 1987—following a 1-year hiatus during which none were prepared—the reports have been submitted annually in March.

Results in Brief

New Project Status Report criteria for the selection of projects for reporting, the timing and duration of the reports, and the report format and structure have been established jointly by NASA's Comptroller's Office and the four requesting Committees. These criteria integrate NASA's reporting capabilities with the Committees' requirements for cost, schedule, and performance information on NASA's major projects.

NASA is able to produce the reports using the new criteria. However, additional internal controls over the process employed to develop Project Status Reports are needed to ensure their reliability. Unreliable project status information could mislead the reports' users, who rely on them to help make resource allocation decisions.

Principal Findings

New Criteria Have Been Established for NASA's Project Status Reports

New criteria for NASA's Project Status Reports have been established jointly by NASA Comptroller officials and the requesting Committees. NASA is able to develop the reports meeting the new criteria, and the resulting information satisfies the Committees' requirements for cost, schedule, and performance information on NASA's major projects.

Project Status Reports will now be developed on all NASA projects that meet the NASA Budget Administration Manual's definition of a project and are estimated to cost $200 million or more to research and develop. Starting on March 15, 1990, the reports will be prepared biannually—as of March 15 and July 30. Following a project's new-start approval, the reports will begin the first March after the project's estimate reaches the cost threshold and end with the report following project completion.

The revised Project Status Report has six parts. Part I is a narrative status report highlighting the project's current progress and problems. Parts II through V track the cost, funding, schedule, and performance of the project, as measured against NASA's estimates. Part VI presents key project background information. Appendix II illustrates the revised Project Status Report form.

Project Status Report Process Needs Additional Internal Controls

NASA has never formalized its process to develop Project Status Reports by developing written guidelines or specifying responsibilities for developing the reports. Guidance is informal and vague, as GAO found when it examined the 1988 report on the Magellan mission to Venus—one of seven 1988 Project Status Reports that year. Some of the Magellan data was inaccurate, out-of-date, and unverifiable. For example, some cost estimates were wrong; some milestones were not the most current; the latest acquisition cost estimate lacked documentation; the source of the upper stage development estimate was unknown; and NASA officials could not tell GAO who had developed the "Progress, Problems and Pending Decisions" narrative or upon what data it was based. NASA officials disagreed with GAO's findings but provided no documentation to support their position.

Recommendation

GAO recommends that the NASA Administrator examine NASA's process to develop Project Status Reports and establish the internal controls necessary to ensure that the Project Status Reports using the new criteria are reliable.

Agency Comments

As requested, GAO did not ask NASA to comment officially on a draft of this report. However, the views of responsible officials were sought throughout the course of GAO's work, and their comments were incorporated where appropriate.

NASA officials have agreed to the new criteria and are committed to reviewing and, if necessary, revising the report development process to ensure that the Project Status Reports delivered to the Congress are reliable. They have also agreed to prepare written guidelines to assist in the development of the reports.

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Abbreviations

DDT&E	Design, Development, Test and Evaluation
FACS	Financial and Contractual Status
GAO	General Accounting Office
HUD	Housing and Urban Development
MO&DA	Mission Operations and Data Analysis
NASA	National Aeronautics and Space Administration
PSR	Project Status Report
TDRSS	Tracking and Data Relay Satellite System
VA	Veterans Affairs

Chapter 1

Introduction

Background

In our report on NASA Issues (GAO/OCG-89-15TR, Nov. 1988), we identified the National Aeronautics and Space Administration's (NASA) incomplete project cost reporting as an issue to be considered by the incoming administration and the Congress. While developing that report, we found that NASA had the capability to report more complete project costs. NASA has provided, on occasion since the mid-1970s, Project Status Reports (PSR) on selected NASA projects at the request of the Chairman of the Subcommittee on VA, HUD and Independent Agencies, Senate Committee on Appropriations . The purpose of the reports was to provide timely information on the cost, schedule, and performance of selected major projects to assist the Subcommittee in its review of NASA's budget requests. The projects were selected in an ad hoc manner, according to the Subcommittee's interests.

The NASA Comptroller's Office is currently the NASA focal point responsible for preparing the PSRs. Once NASA receives a Subcommittee request for a PSR, the Comptroller's Office tasks the appropriate NASA program offices to submit PSR information, collects and combines the data provided, and submits the PSR to the Subcommittee.

The PSRs, which were patterned after the Department of Defense's Selected Acquisition Reports, include cost, schedule, and technical information under the following subject headings: mission and description; progress, problems, and pending decisions; mission/technical characteristics; scheduled milestones; program acquisition cost; funding; support costs; and other agency and foreign participation.

The PSRs were initially submitted on January 30 and July 31 of each year. Beginning in 1987, however—following a 1-year hiatus during which none were prepared—NASA began to submit PSRs annually in March. From 1976 through 1989, NASA developed 146 PSRs on 17 different projects. A complete schedule of these PSRs appears in appendix I.

Objectives, Scope, and Methodology

NASA's four principal oversight Committees[1] requested that we review NASA's ability to produce PSRs that meet their requirements for reliable cost, schedule, and performance information on major projects. As part of this request, we helped the Committees and NASA agree upon criteria for project selection and report timing, duration, format, and contents. We also reviewed NASA's current process for developing these reports.

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[1] The four requesting Committees are the Subcommittee on VA, HUD and Independent Agencies, Senate Committee on Appropriations; the House Committee on Science, Space and Technology; the Subcommittee on VA, HUD and Independent Agencies, House Committee on Appropriations; and the Subcommittee on Science, Technology and Space, Senate Committee on Commerce, Science, and Transportation.

To ensure NASA's ability to develop the new PSR, we worked with personnel from NASA's Comptroller's Office and used their comments in the development of the Project Status Report criteria. We also integrated NASA's comments with the Committees' requirements to establish a new set of mutually agreeable PSR criteria. Using the requesters' specifications, we interviewed representatives from each NASA program office to identify projects potentially eligible for reporting.[2]

To assess the reliability of the existing Project Status Report and the process used to prepare it, we selected one of the seven 1988 PSRs—the space science mission to Venus named Magellan—as a case study.[3] A NASA Comptroller official told us that the process used to prepare PSRs for space science projects—such as Magellan—was representative of the process used to prepare all NASA PSRs. We chose the space science project Magellan because it had a nearly completed and relatively uncomplicated development history.

We focused our work on NASA's Comptroller's Office and the Office of Space Science and Applications at NASA Headquarters in Washington, D.C. We also performed work at the Jet Propulsion Laboratory in Pasadena, California.

As requested, we did not obtain written comments on a draft of this report. However, we obtained the views of agency officials and considered them throughout the preparation of this report. Our work was performed from November 1988 to November 1989 in accordance with generally accepted government auditing standards.

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[2] NASA has five program offices—the Office of Space Science and Applications, the Office of Space Flight, the Office of Aeronautics and Space Technology, the Office of Space Station, and the Office of Space Operations.

[3] In 1988 NASA prepared PSRs for the Ulysses, Mars Observer, Galileo, Hubble Space Telescope, National Aerospace Plane, Upper Atmospheric Research Satellite, and Magellan projects.

Chapter 2

New Project Status Report Criteria

New criteria for NASA's Project Status Reports have been jointly established and agreed to by NASA Comptroller officials and representatives from NASA's four oversight Committees. These criteria address the selection of projects for reporting, specify the timing and duration of reports, and set out their format and structure. By adhering to the criteria, NASA will provide the Committees with timely cost, schedule, and performance information on its major projects.

PSR Selection, Timing, and Duration

PSRs will be prepared on all NASA projects that (1) meet the NASA Budget Administration Manual's definition of a project and (2) are estimated to cost $200 million or more to research and develop. The NASA manual defines a project as

> "... an undertaking with a scheduled beginning and ending, which normally involves one of the following primary purposes: (1) the design, development and demonstration of major advanced hardware items; (2) the design, construction and operations of a new launch vehicle (and associated ground support) during the research and development phase; and (3) the construction and operation of one or more aeronautical or space vehicles and necessary ground support in order to accomplish a scientific or technical objective."

The Committees' representatives set a minimum cost criterion to limit PSRs to NASA's higher cost projects. The cost criterion was set at a minimum research and development cost estimate of 200 million real-year dollars.[1] This cost criterion can be re-examined in future years and adjusted upward to account for inflation.

Using these criteria, we asked officials in each of NASA's program offices to supply lists of their currently eligible projects. On the basis of these lists and in consultation with the Committees' representatives, we prepared a list of 19 projects eligible for the next PSR process beginning in March 1990, as shown in table 2.1.

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[1] Real-year dollars include estimates of inflation in future years.

Table 2.1: NASA Projects Eligible for March 1990 PSRs, Listed by NASA Program Office

Program office	Project
Space Science and Applications	Advanced X Ray Astrophysics Facility Advanced Communications Technology Satellite Comet Rendezvous Asteroid Flyby/Cassini[a] Extreme Ultraviolet Explorer Galileo Gamma Ray Observatory Global Geospace Science Hubble Space Telescope Magellan Mars Observer Ocean Topography Experiment Ulysses Upper Atmospheric Research Satellite
Space Flight	Advanced Solid Rocket Motor Orbital Maneuvering Vehicle Replacement Orbiter
Space Station[b]	Flight Telerobotic Servicer
Aeronautics and Space Technology	National Aerospace Plane
Space Operations	Tracking and Data Relay Satellite System

[a] Although the Comet Rendezvous Asteroid Flyby and Cassini are two separate missions, NASA is requesting funding as if they were one project. As they progress in development, the cost estimates and milestones may begin to diverge, and it will become necessary to develop separate PSRs for each project.

[b] The Committees' representatives and NASA officials agreed that the Space Station Capital Development Plan would be used in lieu of a PSR for the space station. This plan—as directed by the 1988 NASA Authorization Act—includes a statement outlining the projected total cost, schedule, and configuration of the space station. It is to be prepared each of the fiscal years 1989 through 1996 and to be submitted along with the President's annual NASA budget request.

The Committees' representatives and NASA officials agreed that the PSRs for projects meeting the eligibility criteria would be prepared biannually—as of March 15 and July 30—so they are available for use both at the beginning of the budget review process and at the end during the final framing of the spending bills. These due dates, which closely coincide with NASA's biannual cost estimating process (on March 1 and July 1), will enable the PSRs to reflect current information.

PSRs on eligible projects will be submitted during the first March following congressional new-start approval or later when they reach the $200 million cost threshold[1] and end with a final PSR after project completion. For the purpose of the PSR, project completion is defined as the time when NASA can assess how well the project has achieved its objectives. See appendix III for a more detailed discussion of project completion.

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[1] A PSR is prepared for a project when it reaches the $200 million cost threshold for its total estimated research and development. Sometimes a project may not meet this threshold until months or years after the initial congressional new-start approval.

Format for the New PSR

The Committees' representatives approved the following six-part PSR format:

- Part I - Project Status,
- Part II - Project Cost Estimates,
- Part III - Funding for Project Development,
- Part IV - Principal Milestones,
- Part V - Project Goals and Objectives, and
- Part VI - Project Background.

Each part is briefly described below. Appendix II provides an illustration of the revised PSR, and in appendix III we describe its data elements and suggest source documents for its development.

"Part I - Project Status" calls for a brief narrative summary highlighting the project's most recent progress and any problems identified in other parts of the PSR. This section also requires a description of corrective actions taken or planned by NASA to mitigate the negative impacts of any problem identified.

"Part II - Project Cost Estimates" requires that the amount and reason for project cost growth be tracked over time. It requests two project cost estimate baselines—the initial project cost estimate that is developed when NASA first requests new-start approval and the development cost estimate that NASA managers prepare after they have a fuller picture of project costs (usually at the time of a project's Preliminary Design Review).[1]

Part II requires that NASA cost estimates be tracked over time for the NASA cost components—costs for the primary program office and the supporting program offices. Estimates of project costs incurred outside of NASA (by other U.S agencies and other participants) will also be listed in Part II. Because these estimates are developed by NASA's partners, NASA officials will only be responsible for reporting the latest estimates provided to them by these partners.

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[1] The Preliminary Design Review is NASA's technical review of the project's basic design to ensure its producibility and compatibility with the project's requirements

"Part III - Funding for Project Development" requires that the project's research and development funding be displayed in three ways—citing what has been funded, what is currently available, and what is needed for the future.

"Part IV - Principal Milestones" requires that the progress towards and the completion of key milestones be charted. Key milestones include

- the date of the announcement of science opportunity to the community of scientists outside of NASA (if applicable),
- the date that development contracts are awarded,
- the date when all Preliminary Design Reviews are completed,
- the date that all Critical Design Reviews are completed,[4]
- the launch date, and
- the date of project completion.

Part IV also requires two baselines—the "initial project estimate" and an updated "development estimate."

"Part V - Project Goals and Objectives" requires a summary of the project's goals and objectives (technological and/or scientific), as defined by NASA

- in its initial project presentation to the Congress,
- in its project development estimate, and
- in its assessment of final project performance.

"Part VI - Project Background" requires project information regarding

- the project's relationship to NASA's strategic plan and its contribution to other NASA missions;
- the general background of the project, including when it was approved as a new-start and the time and amount spent on it during "advanced studies";[5]
- the NASA components primarily involved and the extent of their involvement;
- the prime contractors and what they are to deliver to NASA; and
- the roles, responsibilities, and contributions of other involved participants, such as domestic and foreign commercial and academic entities.

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[4] The Critical Design Review is NASA's review of the detailed design when it is approximately 80 percent complete to ensure that the project design is in compliance with NASA requirements.

[5] "Advanced studies" is NASA's term for all pre-project research activities.

Conclusion

New criteria for the selection of projects for PSR reporting, the timing and duration of the PSR reports, and the PSR report format and structure have been agreed to by NASA and the requesting Committees. The criteria integrate NASA's reporting capabilities with the Committees' requirements for timely cost, schedule, and performance information on NASA's major projects.

Chapter 3

NASA Must Ensure the Development of a Reliable PSR

Although NASA has agreed to follow the new PSR criteria, NASA needs additional internal controls to ensure the preparation of reliable PSRs. NASA has had an informal process for developing PSRs. In attempting to trace and verify the information in one representative PSR—the March 1988 Magellan PSR—we found that NASA needs to improve that process. NASA must ensure that there are adequate internal controls in place to guide the preparation and processing of PSRs that are current, accurate, complete, and satisfy the basic criteria outlined in chapter 2.

PSRs Need to Be Reliable

Funding requirements for NASA are expected to rise dramatically in the 1990s and could triple by the year 2000 if some recently proposed research and development initiatives such as a lunar outpost or a staffed Mars expedition are adopted. In the current budget deficit environment, budget decisionmakers face increasingly difficult decisions on NASA budget allocations. They must decide what civil space projects will be undertaken and the pace at which they will be funded. Reliable cost, schedule, and performance information on NASA's major projects can help in making these decisions.

NASA provides the Congress with information on its research and development activities through testimony, budget estimates, and various reports; however, none of these methods provides the comprehensive and focused information the revised PSR will provide. The PSR will provide congressional decisionmakers with a concise picture of the cost, schedule, and performance status of NASA's major projects.

Congressional use of the PSR should reduce the frequency and volume of ad hoc information requests to NASA's project managers. For example, before the annual budget hearings, one of NASA's oversight Subcommittees typically requests projected total cost estimates for all major projects, information that another Subcommittee also requests in reviewing project status. These types of requests can be satisfied by the revised PSR. However, for the PSR to be a viable alternative to many ad hoc requests for information, as well as to serve as a reliable source of cost, schedule, and performance information, it must contain accurate, complete, and current information.

PSR Process Needs Additional Internal Controls

In order to understand NASA's reporting capabilities, we selected the March 1988 Magellan PSR as a case study and attempted to trace its data and to identify its supporting documentation. We found the PSR process to be vague and confusing.

NASA does not have formal instructions specifying the method for PSR development, the responsibilities of the individual NASA program offices involved, or procedures for PSR verification and review. Furthermore, none of the Comptroller and program office officials we interviewed could completely explain the informal PSR procedures being used or identify all the individuals responsible for the preparation of specific PSR information or the sources of such information.

The procedures employed by NASA to produce a PSR did not allow us to verify the accuracy of project information. NASA Comptroller officials told us that PSR information was generally prepared by updating a copy of the last PSR with handwritten corrections. NASA project and resource management officials told us that several program offices may comment on a particular PSR in this manner, and NASA Comptroller officials responsible for reviewing the PSRs have no record of where certain PSR information originated.

In tracing the sources of information used in the March 1988 Magellan PSR, we found data that was wrong, out-of-date, and unverifiable:

- The upper stage "prior years" and "FY 1988" funding figures were wrong. The figure reported in the March 1988 Magellan PSR for upper stage "prior year" funding was $15.2 million. According to NASA officials, it should have been $20.0 million. The funding for "FY 1988" was shown as $32.5 million, when it actually was $27.7 million, according to NASA Comptroller officials. The NASA Comptroller official responsible for these figures told us that the person who prepared them must have made a mathematical error.
- The milestones reported in the PSR for "Delivery of Spacecraft to KSC [Kennedy Space Center]" and "Launch" had not been updated with the latest information available at the time of the PSR's development. The PSR, which stated that its data was current as of January 31, 1988, indicated "Delivery of Spacecraft to KSC" during the first quarter of calendar year 1988. Yet the December 1987 Project Management Report—which was accurate according to NASA Comptroller officials—listed this date as the fourth quarter of 1988. Similarly, the PSR listed "Launch" for the second quarter of calendar year 1988, yet the Project Management Report listed it for the first quarter of 1989. A NASA Comptroller official

explained that these discrepancies had resulted from typographical errors.

Finally, unverifiable information was pervasive in the Magellan PSR. For example, the NASA officials responsible for the material in the "Progress, Problems and Pending Decisions" section of the PSR could not tell us who had prepared it or upon what data it was based. Similarly, NASA Comptroller officials did not know the origin of the development estimate for the Centaur upper stage. NASA officials also told us that the "Current Estimate" for Magellan acquisition cost had not been documented.

NASA officials disagreed with our finding that some data in the 1988 Magellan PSR was wrong, out-of-date, and unverifiable. Although they promised to provide us with documentation that would support this position, the evidence was not forthcoming.

Conclusions

During our review of the March 1988 Magellan PSR, we found data that was inaccurate, out-of-date, and unverifiable. We also found that the current process used to develop PSRs needs additional internal controls to ensure reliable PSR data. If the PSR data is unreliable, the report cannot be used as a basis for sound resource allocation decisions. In order to ensure the reliability and usefulness of the PSRs, NASA needs to establish adequate internal controls for preparing, processing, and reviewing PSRs. These controls are especially important as PSRs change from ad hoc reports on relatively few projects to routine, biannual reports on many more projects.

Specific internal controls to strengthen NASA's development of PSRs that meet the new criteria described in chapter 2 should begin with NASA's developing and institutionalizing PSR guidelines. These guidelines should

- identify an accountable NASA focal point who will ensure that PSRs are reliable and meet the prescribed criteria for project eligibility, report timing and duration, format, and contents;
- identify the NASA offices responsible for each specific part of the PSR;
- specify the sources of data to be used when preparing the PSR;
- establish verification and review procedures; and
- establish and maintain a complete historical file of PSRs.

NASA officials have agreed to review and, if necessary, revise the current process used to develop the PSRs to ensure that the PSRs delivered to the

Congress are reliable. In doing so, NASA has also agreed to develop written guidelines for preparing PSRs and to base the guidelines on the information provided in this report.

Recommendation to the NASA Administrator

We recommend that the NASA Administrator examine NASA's process to develop Project Status Reports and establish the internal controls necessary to ensure that the Project Status Reports using the new criteria are reliable.

Project Status Reports Filed in the NASA Comptroller's Office

Project	Submission dates
1 Space Shuttle	1/30/76, 1/31/77, 7/31/77, 1/31/79, 3/05/80, 7/31/80, 1/31/81, 7/31/81, 1/31/82, 7/31/82, 1/31/83
2 HEAO A-C	1/30/76, 7/31/76, 1/31/77, 7/31/77, 1/31/78, 7/31/78, 1/31/79, 7/31/79, 3/05/80, 7/31/80
3 Mariner Jupiter/Saturn Voyager	1/30/76, 7/31/76, 1/31/77, 7/31/77, 1/31/78, 7/31/78, 1/31/79, 7/31/79, 3/05/80, 7/31/80, 1/31/81, 7/31/81, 1/31/82
4 Pioneer Venus	1/30/76, 7/31/76, 1/31/77, 7/31/77, 1/31/78, 7/31/78, 1/31/79, 7/31/79
5 SEASAT A or 1	1/30/76, 7/31/76, 1/31/77, 7/31/77, 1/31/78, 7/31/78, 1/31/79, 7/31/79
6 LANDSAT-C	1/30/76, 7/31/76, 1/31/77, 7/31/77, 1/31/78, 7/31/78, 1/31/79, 7/31/79
7 LANDSAT-D	1/31/78, 7/31/78, 1/31/79, 7/31/79, 3/05/80, 7/31/80, 1/31/81, 7/31/81, 1/31/82, 7/31/82, 1/31/83, 7/31/83
8 Hubble Space Telescope	1/31/78, 7/31/78, 1/31/79, 7/31/79, 3/05/80, 7/31/80, 1/31/81, 7/31/81, 1/31/82, 7/31/82, 1/31/83, 7/31/83, 7/31/84, 1/31/85, 3/25/87, 3/23/88, 3/30/89
9 Galileo	1/31/78, 7/31/78, 1/31/79, 3/05/80, 7/31/80, 1/31/81, 7/31/81, 1/31/82, 7/31/82, 1/31/83, 7/31/83, 1/31/84, 7/31/84, 1/31/85, 3/25/87, 3/23/88, 3/30/89
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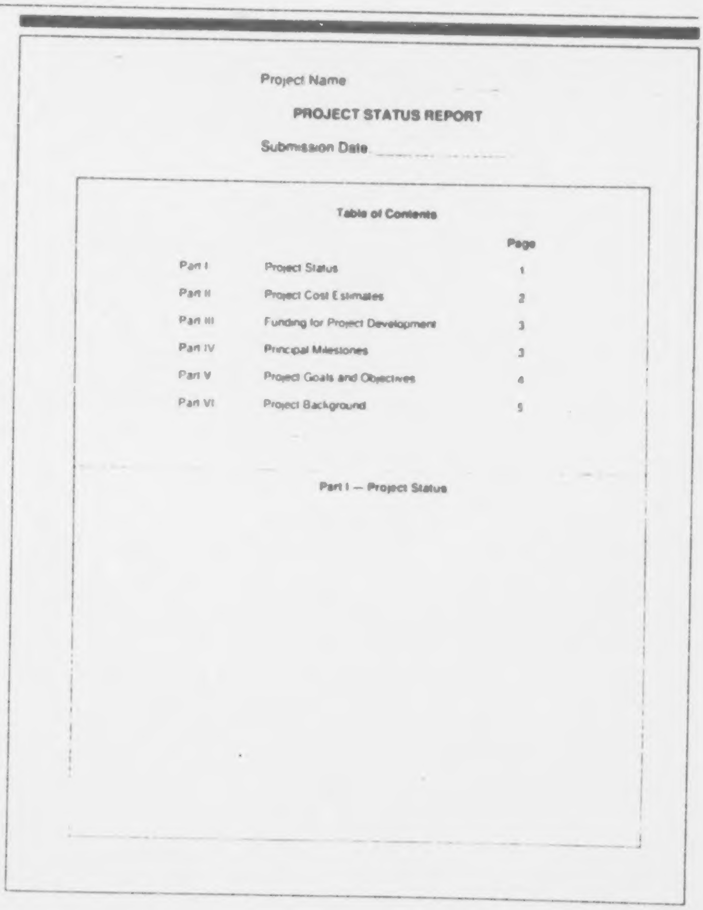
11 Gamma Ray Observatory	1/31/81, 7/31/81, 1/31/82, 7/31/82, 1/31/83, 7/31/83, 1/31/84, 7/31/84, 1/31/85
12 Magellan	1/31/84, 7/31/84, 1/31/85, 3/25/87, 3/23/88, 3/30/89
13 Upper Atmospheric Research Satellite	3/25/87, 3/23/88, 3/30/89
14 Mars Observer	3/25/87, 3/23/88, 3/30/89
15 National Aerospace Plane	3/25/87, 3/23/88, 3/30/89
16 Comet Rendezvous Asteroid Flyby/ Cassini	3/30/89
17 Advanced X-Ray Astrophysics Facility	3/30/89

Appendix II

Project Status Report Form



Project Name

PROJECT STATUS REPORT

Submission Date ____________

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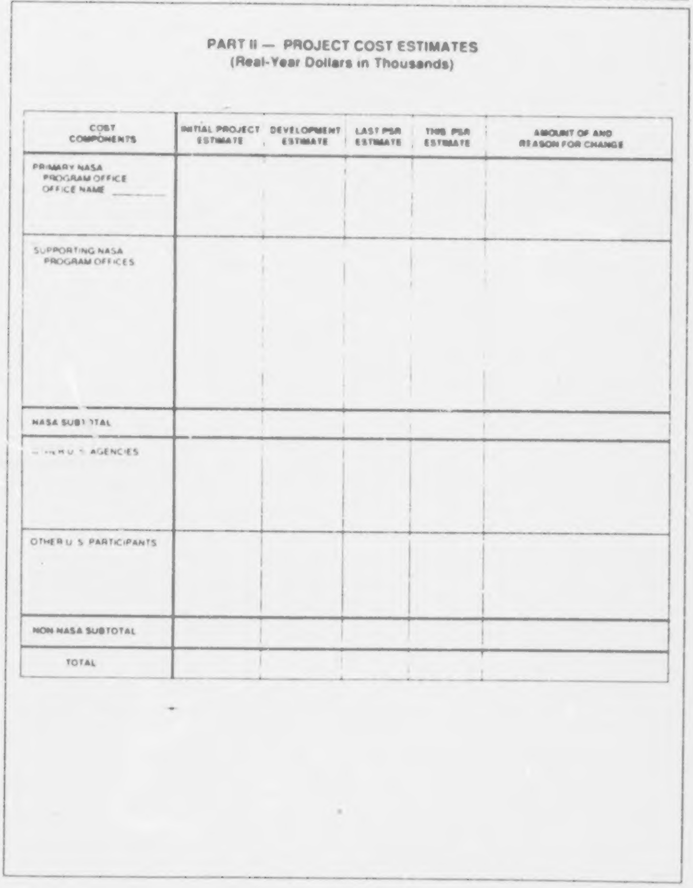
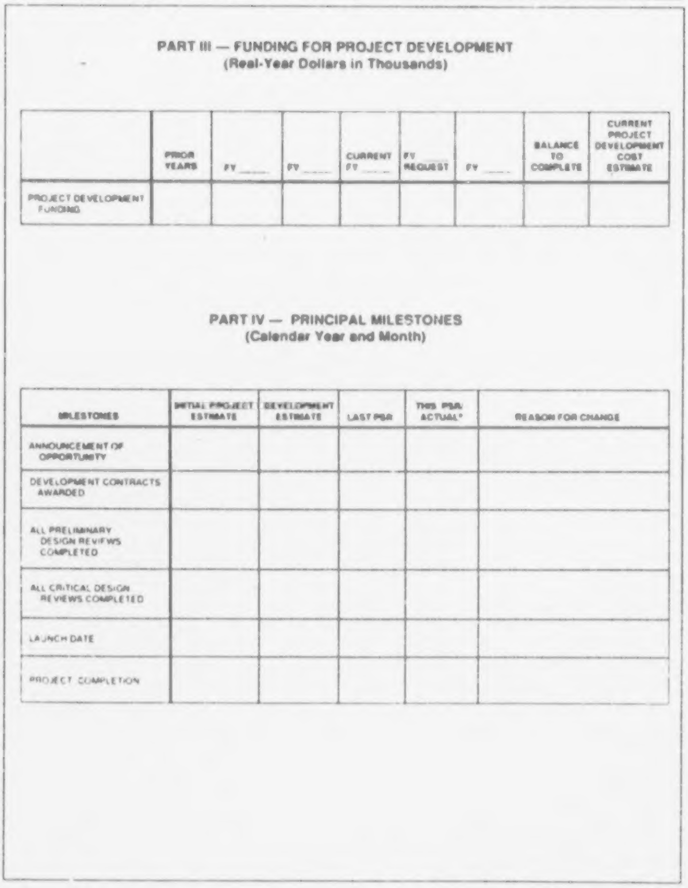
Part I	Project Status	1
Part II	Project Cost Estimates	2
Part III	Funding for Project Development	3
Part IV	Principal Milestones	3
Part V	Project Goals and Objectives	4
Part VI	Project Background	5

Part I — Project Status



PART II — PROJECT COST ESTIMATES
(Real-Year Dollars in Thousands)

COST COMPONENTS	INITIAL PROJECT ESTIMATE	DEVELOPMENT ESTIMATE	LAST PSR ESTIMATE	THIS PSR ESTIMATE	AMOUNT OF AND REASON FOR CHANGE
PRIMARY NASA PROGRAM OFFICE OFFICE NAME ________					
SUPPORTING NASA PROGRAM OFFICES					
NASA SUBTOTAL					
OTHER U.S. AGENCIES					
OTHER U.S. PARTICIPANTS					
NON-NASA SUBTOTAL					
TOTAL					

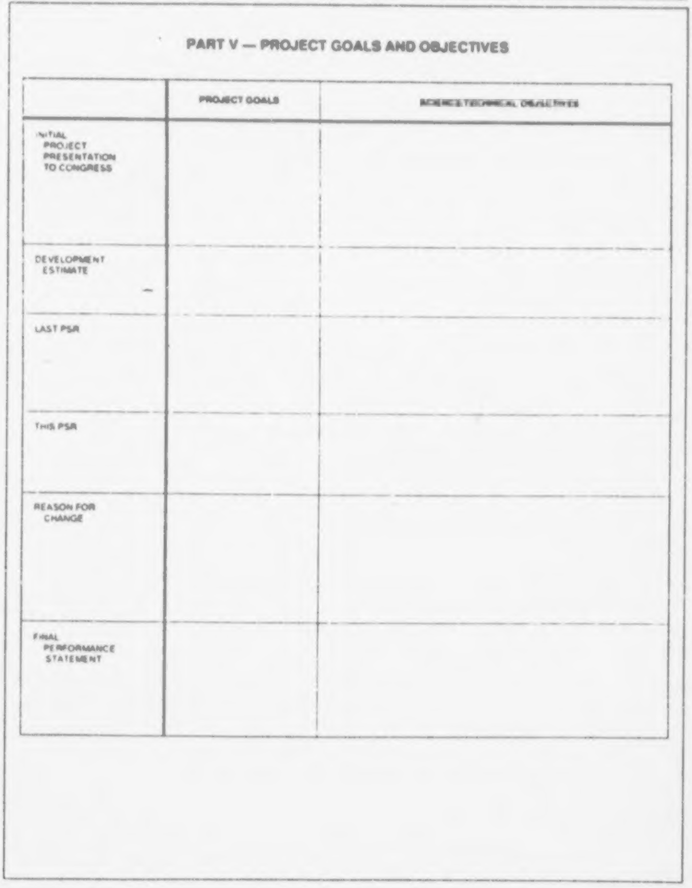


PART III — FUNDING FOR PROJECT DEVELOPMENT
(Real-Year Dollars in Thousands)

	PRIOR YEARS	FY ____	FY ____	CURRENT FY ____	FY ____ REQUEST	FY ____	BALANCE TO COMPLETE	CURRENT PROJECT DEVELOPMENT COST ESTIMATE
PROJECT DEVELOPMENT FUNDING								

PART IV — PRINCIPAL MILESTONES
(Calendar Year and Month)

MILESTONES	INITIAL PROJECT ESTIMATE	DEVELOPMENT ESTIMATE	LAST PSR	THIS PSR/ ACTUAL*	REASON FOR CHANGE
ANNOUNCEMENT OF OPPORTUNITY					
DEVELOPMENT CONTRACTS AWARDED					
ALL PRELIMINARY DESIGN REVIEWS COMPLETED					
ALL CRITICAL DESIGN REVIEWS COMPLETED					
LAUNCH DATE					
PROJECT COMPLETION					



PART V — PROJECT GOALS AND OBJECTIVES

	PROJECT GOALS	SCIENCE/TECHNICAL OBJECTIVES
INITIAL PROJECT PRESENTATION TO CONGRESS		
DEVELOPMENT ESTIMATE		
LAST PSR		
THIS PSR		
REASON FOR CHANGE		
FINAL PERFORMANCE STATEMENT		

PART VI — PROJECT BACKGROUND

PROJECT'S RELATIONSHIP TO NASA'S STRATEGIC PLAN

GENERAL BACKGROUND

PRIMARY NASA COMPONENTS AND THEIR RESPONSIBILITIES

PRIME CONTRACTORS AND THEIR RESPONSIBILITIES

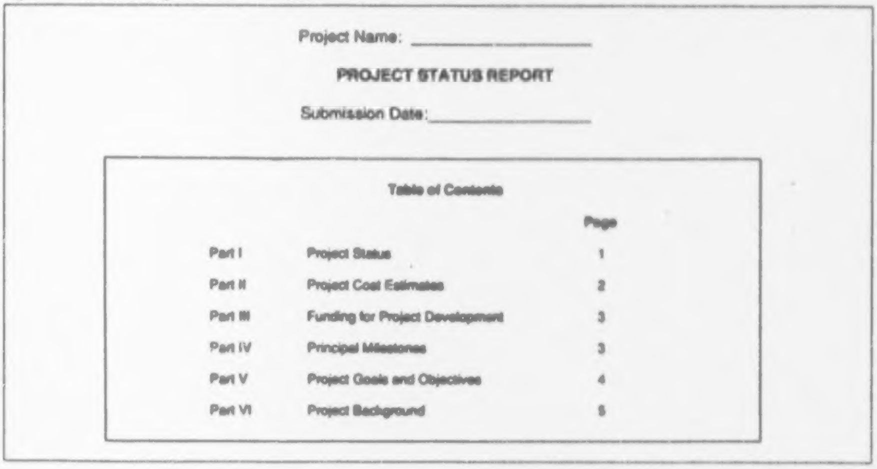
OTHER PARTICIPANTS AND THEIR RESPONSIBILITIES

Completing the PSR Form

This appendix describes the contents of the revised PSR form and, where appropriate, identifies source documents that could be used to complete it. Whenever possible, information reported in the PSR should correspond to information contained in NASA's internal automated cost reporting system.[1]

As depicted in figure III.1, the heading information includes the project name and the date the PSR is submitted to the Committees. The table of contents for the PSR is self-explanatory. Each individual PSR part is discussed below, including an explanation of what information should be included in each of the parts.

Figure III.1: PSR Heading and Table of Contents



Project Name: ____________________

PROJECT STATUS REPORT

Submission Date:____________________

Table of Contents

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Part I	Project Status	1
Part II	Project Cost Estimates	2
Part III	Funding for Project Development	3
Part IV	Principal Milestones	3
Part V	Project Goals and Objectives	4
Part VI	Project Background	5

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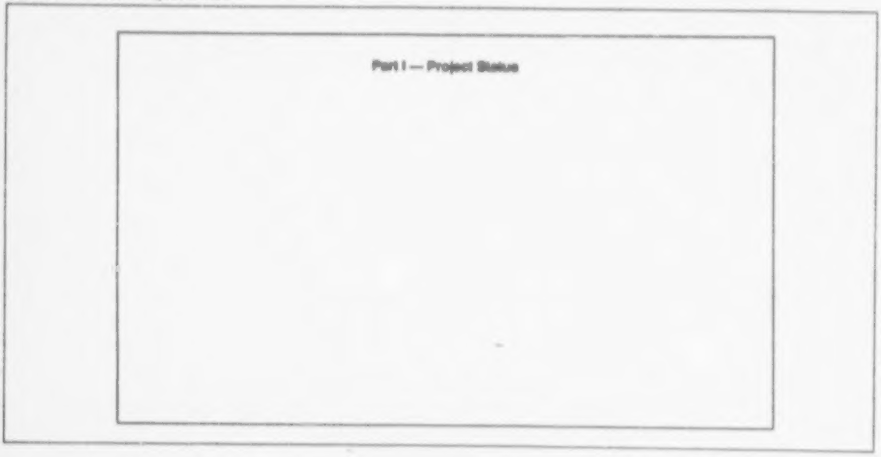
[1] NASA's Division of Financial Management maintains the Financial and Contractual Status (FACS) database, which reports all NASA financial activity. This database employs an automated Agencywide Coding Structure system, which identifies NASA's financial activities by project.

Part I - Project Status

"Part I - Project Status" summarizes the progress and/or problems with a project's cost, schedule, and performance. Part I explains NASA's corrective actions planned to mitigate the negative effects of any problem on the project's progress, such as requesting additional or reprogramming existing funding or de-scoping project objectives. The narrative should be tailored to fit in the space provided on the first page of the PSR. (See figure III.2.)

Figure III.2: Part I - Project Status

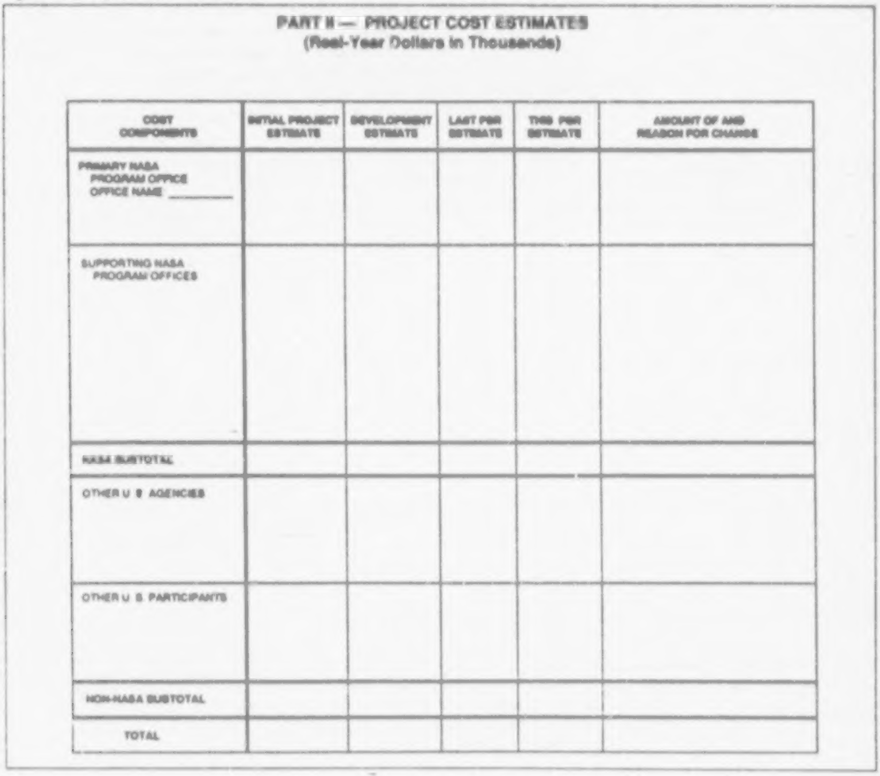


Part I — Project Status

Part II - Project Cost Estimates

"Part II - Project Cost Estimates" tracks the amount of and reason for a project's cost growth over time. Project cost components are listed vertically down the left-hand column and then tracked horizontally by the estimate/change columns. (See figure III.3.)

Figure III.2: Project Cost Estimates



PART II — PROJECT COST ESTIMATES
(Real-Year Dollars in Thousands)

COST COMPONENTS	INITIAL PROJECT ESTIMATE	DEVELOPMENT ESTIMATE	LAST PSR ESTIMATE	THIS PSR ESTIMATE	AMOUNT OF AND REASON FOR CHANGE
PRIMARY NASA PROGRAM OFFICE OFFICE NAME ________					
SUPPORTING NASA PROGRAM OFFICES					
NASA SUBTOTAL					
OTHER U. S. AGENCIES					
OTHER U. S. PARTICIPANTS					
NON-NASA SUBTOTAL					
TOTAL					

NASA Cost Components

The NASA cost components include the "Primary NASA Program Office" and the "Supporting NASA Program Offices." (See figure III.3.) The "Primary NASA Program Office" is the program office at NASA Headquarters responsible for the oversight of research and development costs that are unique to the project. The presentation of these costs should be consistent with NASA's cost reporting terminology and therefore will vary by project. For example, NASA usually displays the primary program costs for a science project, such as Magellan, as "Project Development" and "Mission Operations and Data Analysis" (MO&DA). On the other hand, for an operational project, such as the Tracking and Data Relay Satellite System (TDRSS), NASA may display the primary program costs as "Design, Development, Test and Evaluation" (DDT&E) and "Operational Capability Development."

On the basis of these examples, "Project Development" costs for a science project are costs incurred to develop the spacecraft, the costs of experiments/instruments, and the costs of ground operations. "MO&DA" costs are the costs to operate the spacecraft and to analyze the data transmitted to Earth. For the purposes of the PSR, the MO&DA estimate ends when the mission has completed its original objectives. (We define "Project Completion" in our section on "Milestones," p. 36.)

For a project with an operational objective, "DDT&E" is used to refer to costs incurred to design, develop, test, and evaluate the project. "Operational Capability Development" is the term NASA uses to refer to costs incurred by the primary program office to prepare the system for its full operational capability. For example, "Operational Capability Development" costs for the Tracking and Data Relay Satellite System could include the NASA Budget Estimate line items "Space network operations," "System engineering and support," and "Second TDRSS ground terminal."

The "Supporting NASA Program Offices" estimates include costs incurred by other offices primarily or exclusively in support of the project. Examples include

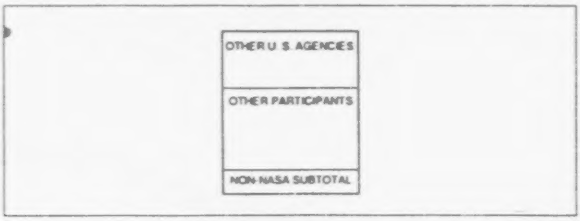
- the costs incurred by the Office of Space Operations in providing any project-related tracking and data acquisition services;
- the marginal cost of a launch when the space shuttle is required to launch a specific project, such as Magellan (currently estimated by NASA officials to be $50 million);

- the costs incurred by the Office of Space Flight to procure required expendable launch vehicle services and upper stage propulsion systems; and
- any costs incurred in the Construction of Facilities appropriation that are unique to the project and not already covered by the "Primary Program Office" cost estimates.

Non-NASA Cost Components

The non-NASA cost components are separated into costs for "Other U.S. Agencies" and for "Other Participants." (See figure III.4.) Because these estimates are developed by NASA's partners, NASA is only responsible for recording the latest cost estimates made available to it; NASA is not responsible for the completeness or accuracy of such estimates.

Figure III.4: Non-NASA Cost Components



"Other U.S. Agencies" estimates include costs to other federal agencies to supply NASA with goods and services in support of a project. For example, the cost incurred by the Department of Energy might include the cost to develop and deliver nuclear power supply equipment.

"Other Participants" estimates include planned expenditures (in equivalent U.S. dollars for foreign participants) by any foreign government and/or international and domestic commercial or academic entities that contribute directly to the project: for example, the estimated cost to the Federal Republic of Germany to provide the propulsion system for the Comet Rendezvous Asteroid Flyby project.

Estimate/Change Columns

The column headings "Initial Project Estimate," "Development Estimate," "Last PSR Estimate," and "This PSR Estimate" help track project estimates over time. The "Amount of and Reason for Change" column explains any change between the last and current PSRs. (See figure III.5.) Similar headings are used again in "Part IV - Principal Milestones" to track the project's schedule and in "Part V - Project Goals and Objectives" to track the project's performance. Therefore, the following discussion on estimate/change columns should also be used when completing those parts of the PSR.

Figure III.5: Part II - Column Headings

INITIAL PROJECT ESTIMATE	DEVELOPMENT ESTIMATE	LAST PSR ESTIMATE	THIS PSR ESTIMATE	AMOUNT OF AND REASON FOR CHANGE

The first column, "Initial Project Estimate," displays the original cost estimates NASA presented to the Congress when it obtained approval to begin the project. NASA's "Project Initiation Agreement" is a good source for this information, since it is the result of NASA's non-advocate cost reviews preceding the congressional new-start presentation. Although the "Primary NASA Program Office" cost estimate will be included, the "Supporting NASA Program Offices" and non-NASA cost estimates may not be fully available until NASA has a more complete picture of the project's costs.

The "Development Estimate" completes and updates the "Initial Project Estimate" by identifying the remaining cost components and by refining the original cost estimates. The "Development Estimate" is usually available around the time of the project's Preliminary Design Review. The Preliminary Design Review usually occurs about 2 years after new-start approval.

The "Development Estimate" for the "Primary NASA Program Office" cost estimate, project milestones, and performance and goals statements can be documented from the project's approved "Project Plan" and "Project Approval Document." The "Project Approval Document" can also be used to document the "Supporting NASA Program Offices" cost estimates.

Once established, the "Initial Project Estimate" and the "Development Estimate" will be repeated on all subsequent PERs.

The "Last PER Estimate" lists the estimated amounts shown on the PER preceding the current one. The column labeled "This PER Estimate" displays the most current estimate. The "Amount of and Reason for Change" column displays the difference between the columns "This PER Estimate" and "Last PER Estimate" and provides a brief but specific explanation for this difference. For example, any major design changes should be highlighted. Source documents for any changes and their explanations include the FACS database, Program Operating Plans, and/or the program office's most recent monthly Project Management Report or status reviews.

Part III - Funding for Project Development

"Part III - Funding for Project Development" charts the "Project Development Funding" both historically and prospectively. This funding corresponds to the amount listed by project line item in NASA's Budget Estimates. (See figure III.6.)

Figure III.6: Funding for Project Development

PART III — FUNDING FOR PROJECT DEVELOPMENT
(Real-Year Dollars in Thousands)

	PRIOR YEARS	FY ____	FY ____	CURRENT FY ____	FY ____ REQUEST	FY ____	BALANCE TO COMPLETE	CURRENT PROJECT DEVELOPMENT COST ESTIMATE
PROJECT DEVELOPMENT FUNDING								

The tracking begins with the "Prior Years" amount, which is the total of all project spending beginning in the fiscal year the project first received congressional approval up to 2 fiscal years prior to the current fiscal year. For example, if the current fiscal year is 1990, the "Prior Years" amount would cover all spending up through and including fiscal year 1987. Information from NASA's FACS database can document this entry.

"Project Development Funding" for the current and the previous 2 fiscal years—which are identified as "Current FY 1990," "FY 1989," and "FY 1988" in our example—should correspond to amounts recorded in NASA's most current Operating Plans (Op Plan) for those years. The figure entered as "Fiscal Year Request" should correspond to the current NASA budget request—which would be FY 1991 in our example. The next "FY " column—"FY 1992" in our example—presents one estimated outyear. The "Balance to Complete" column records the difference between the total "Current Project Development Cost Estimate" and the sum of all preceding entries in Part III. The "Current Project Development Cost Estimate" total should correspond to the most current "Primary NASA Program Office" development estimate recorded in Part II of the PSR. Figure III.7 presents Part III annotated with the sources of information.

Figure III.7: Instructions for Completing Part III

PART III — FUNDING FOR PROJECT DEVELOPMENT
(Real-Year Dollars In Thousands)

	PRIOR YEARS	FY ____	FY ____	CURRENT FY ____	FY ____ REQUEST	FY ____	BALANCE TO COMPLETE	CURRENT PROJECT DEVELOPMENT COST ESTIMATE
PROJECT DEVELOPMENT FUNDING	FACS	Op Plan	Op Plan	Op Plan	Budget Estimate	Budget Estimate	a	PSR Part II

[a] The "Current Project Development Cost Estimate" minus the total of "Prior Years" and all "FY" columns.

Part IV - Principal Milestones

"Part IV - Principal Milestones" tracks the project's progress towards completion of its principal milestones. The principal milestones are displayed vertically down the left-hand column, and progress is tracked horizontally. (See figure III.8.)

Figure III.8: Principal Milestones

PART IV — PRINCIPAL MILESTONES
(Calendar Year and Month)

MILESTONES	INITIAL PROJECT ESTIMATE	DEVELOPMENT ESTIMATE	LAST PSR	THIS PSR/ ACTUAL*	REASON FOR CHANGE
ANNOUNCEMENT OF OPPORTUNITY					
DEVELOPMENT CONTRACTS AWARDED					
ALL PRELIMINARY DESIGN REVIEWS COMPLETED					
ALL CRITICAL DESIGN REVIEWS COMPLETED					
LAUNCH DATE					
PROJECT COMPLETION					

Milestones

The milestones considered to be principal will vary slightly, depending on the nature of the project. The milestones in Part IV are defined as follows:

- The date of the "Announcement of Opportunity" (if applicable) is the day that the scientific community is invited to participate in a NASA program or project.
- The date of "Development Contracts Awarded" is the date when all prime contracts have been awarded.
- The date of "All Preliminary Design Reviews Completed" is the date that the last project element is reviewed for technical compatibility with the project requirements.[2]

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[2] NASA will usually conduct separate reviews for each project element at each level of management. For example, a deep space science mission will have preliminary and critical design reviews for the spacecraft and for each on-board experiment at the contractor, field center, and NASA Headquarters levels.

- The date recorded as "All Critical Design Reviews Completed" is the date when the last project element is reviewed to ascertain whether the design complies with NASA requirements. The critical design review typically occurs when the detailed design is 90-percent complete.
- The "Launch Date" is the date the space shuttle or expendable launch vehicle is scheduled to launch the project. For a project requiring more than one launch, such as TDRSS, "Final Satellite Launch" may be an appropriate milestone.
- The "Project Completion" date is the date that NASA managers can make a reasonable assessment of the project's final performance in relation to its stated goals and objectives. The "Project Completion" will vary, depending on the nature of these goals and objectives.

For example, the "Project Completion" date for a project with a science goal would be the date that NASA managers are able to make preliminary analyses of how well the data obtained contributes to the project's goals. In the case of Magellan, a NASA scientist told us that they will be able to assess how well the project has fulfilled its stated science goal ("to address fundamental questions regarding the origin and evolution of Venus") when it has completed its objectives (one of which is "to map the planet over a 243 day period—one Venus year"). NASA sometimes refers to the completion of objectives as the "nominal mission complete" date. Therefore, although making a definitive statement on how well Magellan achieved its science goals will require many more years of data analysis, a reasonable "Project Completion" date would be the date that the project has completed its nominal mission.[1]

A different determination for "Project Completion" is made for a project the goal of which is to be put into routine use or to become operational. For example, NASA could identify the project completion date for a space transportation system such as the Advanced Solid Rocket Motor as the "First Operational Flight" or the date when testing is complete and the motor is put into routine use. For a system such as TDRSS, operational status would be achieved when testing of the full constellation of TDRSS satellites is completed. Therefore, "First Operational Use" of the full system could be an appropriate milestone to mark project completion.

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[3] NASA officials told us that a "Final Science Report" is routinely prepared for all science projects after the nominal mission has been completed. This report makes an assessment of the project's achieved goals.

Column Headings

The column headings for Part IV, as shown in figure III.9—"Initial Project Estimate," "Development Estimate," "Last PSR," "This PSR/Actual*," and "Reason for Change"—are similar to those in Part II. (See our discussion of these baselines in our section "Estimate/Change Columns," pp. 33-34.)

Figure III.9: Headings for Tracking Principal Milestones

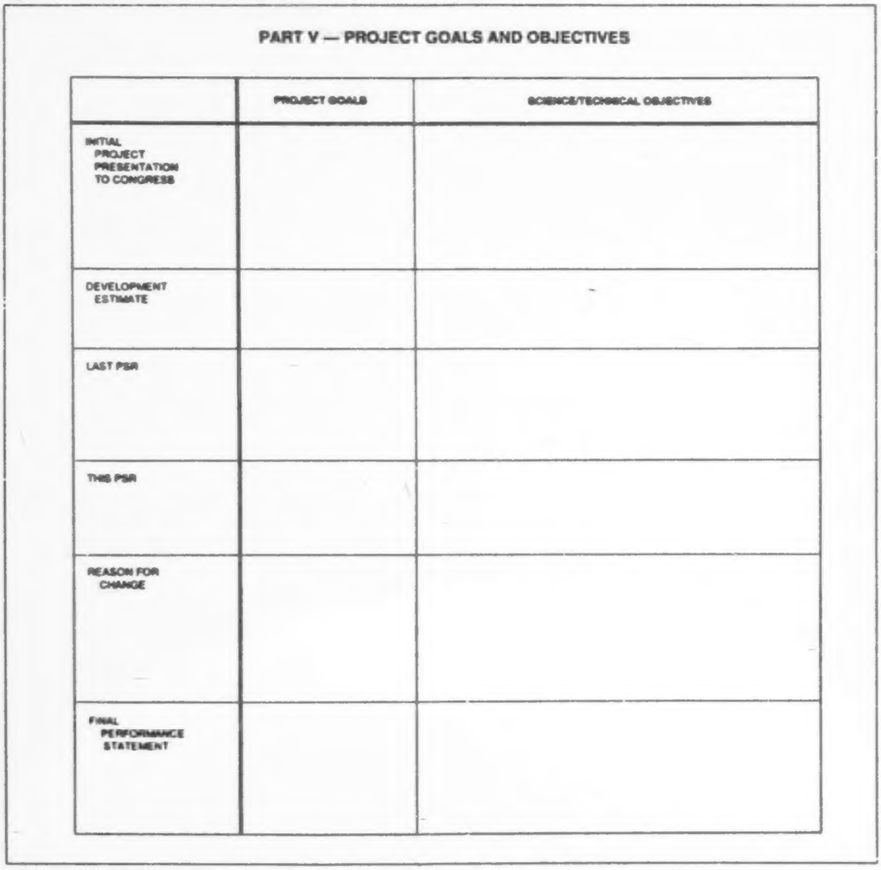
INITIAL PROJECT ESTIMATE	DEVELOPMENT ESTIMATE	LAST PSR	THIS PSR/ ACTUAL*	REASON FOR CHANGE

There is one slight variation from the column headings in Part II: Part IV's "This PSR Estimate/Actual*" column includes a provision for indicating a completed event using an asterisk (*) to signify that the event has occurred.

Part V - Project Goals and Objectives

"Part V - Project Goals and Objectives" tracks the project's progress in meeting its goals and scientific/technical objectives. The points used to track progress in this part are similar to those used in Parts II and IV—that is, "Initial Project Presentation to Congress," "Development Estimate," "Last PSR," "This PSR," "Reason for Change," and "Final Performance Statement." (See our discussion of these baselines in our section "Estimate/Change Columns," pp. 33-34.) Part V, however, differs in the form of presentation. While Parts II and IV list the tracking points horizontally, Part V lists the tracking points vertically down the left-hand column, so there is room to present the narrative information under the two column headings—"Project Goals" and "Science/Technical Objectives." (See figure III.10.) The information should be presented in concise bullet-style phrases and quantified whenever possible. If the information does not fit within the space provided, Part V can be expanded to two pages.

Figure III.10 Project Goals and Objectives



PART V — PROJECT GOALS AND OBJECTIVES

	PROJECT GOALS	SCIENCE/TECHNICAL OBJECTIVES
INITIAL PROJECT PRESENTATION TO CONGRESS		
DEVELOPMENT ESTIMATE		
LAST PSR		
THIS PSR		
REASON FOR CHANGE		
FINAL PERFORMANCE STATEMENT		

"Project Goals" should be stated as the reasons for doing the project. For example, Magellan's project goal is to "to address fundamental questions regarding the origin and evolution of Venus." An example of an operational project goal is provided by the Advanced Solid Rocket Motor project, the goal of which is to increase the space shuttle payload capacity by 12,000 pounds.

The "Science/Technical Objectives" section should specifically and quantifiably describe how the project will achieve its goals. For example, the "Science Objectives" for Magellan, as stated in Magellan's Project Plan and Project Approval Document, are to

- map 70 to 90 percent of Venus, with no systematic gaps except for one pole, with a surface resolution of at least 500 meters and an image resolution of 1 kilometer or better;
- produce maps that reveal the topographic and radar-scattering characteristics of Venus; and
- refine the low-degree and low-order gravity field of Venus and produce high-resolution gravity maps whenever possible.

The "Technical Objectives" section should identify the engineering information, hardware, and instrumentation needed to achieve the project's goals. For example, the technical objectives for the Advanced Solid Rocket Motor could include

- the development of materials and casting processes that can produce a 150-inch diameter motor and
- the use of new non-asbestos insulation materials in conjunction with weldable T-250 steel and High Thrust Prolonged Burn propellant.

As with Parts II and IV, the "Initial Project Presentation to Congress" records the "Project Goals" and "Science/Technical Objectives" statements made by NASA during the new-start approval process and documented in the "Project Initiation Agreement." The "Development Estimate" records the more detailed and further defined statements of goals and objectives that NASA develops for the "Project Plan."

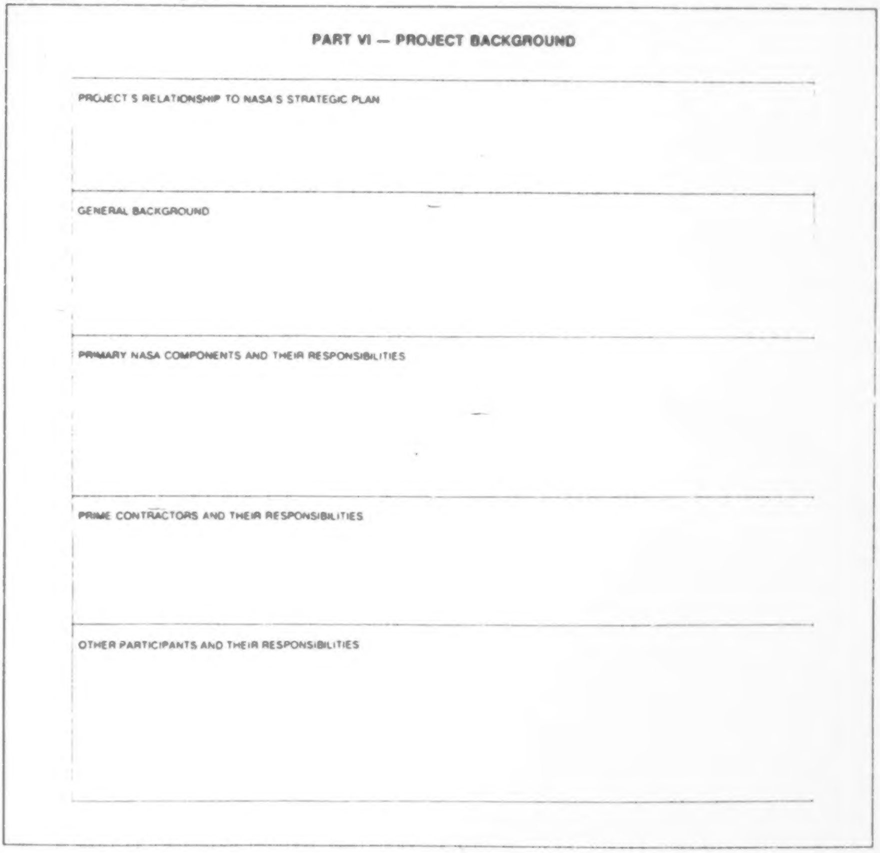
For the sake of brevity, Part V can describe the "Last PSR" and "This PSR" as the "Same as the Development Estimate" or the "Same as the Initial Project Presentation to Congress," when applicable. If a change is made, the "Last PSR" block should list the previous goals and objectives, and the "This PSR" block should list the new ones. Relevant source documents supporting the continuation of or changes in project goals and objectives include a project's monthly Project Management Reports and status reviews. The "Reason for Change" column is used to explain any differences between "This PSR" and the "Last PSR."

The "Final Performance Statement" should assess how well the project fulfilled its stated goals and objectives. For example, Magellan project managers should make a final statement as to what percentage of Venus was mapped, what types of maps were produced and at what resolution, and whether the maps revealed the desired information about Venus. This information can be documented by NASA's "Final Science Report." See our section on "Milestones" for an explanation of this report.

Part VI - Project Background

"Part VI - Project Background" provides information on the "Project's Relationship to NASA's Strategic Plan," the "General Background" of the project, the project's "Primary NASA Components and Their Responsibilities," "Prime Contractors and Their Responsibilities," and "Other Participants and Their Responsibilities." (See figure III.11.)

Figure III.11: Project Background



PART VI — PROJECT BACKGROUND

PROJECT'S RELATIONSHIP TO NASA'S STRATEGIC PLAN

GENERAL BACKGROUND

PRIMARY NASA COMPONENTS AND THEIR RESPONSIBILITIES

PRIME CONTRACTORS AND THEIR RESPONSIBILITIES

OTHER PARTICIPANTS AND THEIR RESPONSIBILITIES

0 1618

The "Project's Relationship to NASA's Strategic Plan" should provide a brief analysis of the relationship between the project's goals as stated in NASA's Strategic Plan (when available) and the project's goals as stated in the primary program office's strategic plan. This section should also describe any project's contribution and/or its relationship to other NASA missions. For example, many scientists consider the origin and evolution of Venus to be similar to the origin and evolution of Earth. Therefore, learning more about the origin and evolution of Venus could contribute to NASA's mission to better understand the planet Earth.

"General Background" should, at a minimum, contain

- the Project Approval Date (the month and year that the project first received congressional new-start approval) and
- the amount of time and money spent on the project before it received new-start approval (during Advanced Studies).

Examples of other information that could be included in "General Background" include

- a description of any plans to extend a science mission, what science goals would be obtained, and what the mission extension would cost and
- an estimate of the annual operating cost for operational projects once they have reached fully operational status.

"Primary NASA Components and Their Responsibilities" should list NASA components (headquarters program offices and field centers) that are extensively involved in the project and their responsibilities.

"Prime Contractors and Their Responsibilities" should list all prime contractors and the goods or services they are obligated to provide.

"Other Participants and Their Responsibilities" should list the roles, responsibilities, and contributions of other involved participants, such as foreign and/or domestic commercial or academic organizations or individuals.

Appendix IV

Major Contributors to This Report

National Security and International Affairs Division, Washington, D.C.	Frank Degnan, Assistant Director Karen L. Kemper, Evaluator-in-Charge Amy L. Manheim, Evaluator
Los Angeles Regional Office	Allan Roberts, Regional Assignment Manager Jeffrey Webster, Site Senior Dawn Sellers, Evaluator

THE SPACE EXPLORATION INITIATIVE:

CURRENT ACTIVITIES,

MULTIPLE AGENCY PARTICIPATION,

AND

MANAGEMENT ALTERNATIVES

Staff Report
Prepared by
Doug Peterson, NASA
Fellow, Summer 1990

Executive Summary

The Space Exploration Initiative is a forcing issue for the nation to confront proposals for our future in space and consider how best to organize the national capability for space. A number of activities are currently underway.

The Outreach program is currently "casting the nets widely" to find new, innovative ideas for returning to the moon and reaching Mars. RAND Corporation is sorting through over 1600 of ideas from industry, universities, associations and the public. The American Institute of Aeronautics and Astronautics (AIAA) has received over 500 responses from members, yet failed to find any 'magic bullets' that would revolutionize program approaches.

The Synthesis Group under General Tom Stafford is synthesizing input from all sources to develop alternative architectures, technology development priorities, and near-term program priorities for SEI. Currently receiving briefings from the agencies, the Group expects to report to NASA and then the National Space Council February/March 1991.

The Advisory Committee on the Future of the U.S. Space Program, chaired by Norman Augustine, scheduled to report by the end of this year, is reviewing the future of the civil space program, including both management issues and program content. The committee is receiving briefings from NASA and a number of other organizations and individuals involved in space.

The Administration has decided to implement SEI with major contributions from the Departments of Energy and Defense in addition to NASA. The program's extremely large size practically demands a multiple agency approach. The DOE labs and defense capabilities fit program requirements in critical areas. Expected defense reductions can be offset by new initiatives in civilian space. Critical capabilities at laboratories and contractors can be maintained rather than lost.

Civilian space activities at Lawrence Livermore National Laboratory (LLNL) appear to be centered around Lowell Wood and his "Great Exploration" Initiative. The greatest contribution thus far is invigorating the discussion of new ideas for SEI.

Sandia National Laboratory (SNL) and Los Alamos National Laboratory are mobilizing for SEI and the staffs are very excited about lunar/Mars roles. Unlike LLNL, both are working closely with NASA in meetings and workshops to identify program strategies, technology requirements/options, and respective capabilities. Each lab has important technology capabilities, such as nuclear propulsion, nuclear power, and radiation protection, etc, that could be quite useful.

The Department of Defense has been approaching SEI at a more measured pace, yet activities have accelerated recently. A task team has inventoried DOD capabilities, identified innovative ideas for SEI and briefed the Stafford group. Potential responsibilities in SEI might be all types space transportation, systems engineering, long-term operations, program management, and logistics.

Despite advantages of multiple agency participation, some disadvantages need careful consideration. First, the complexity of the program can be exacerbated by additional layers of organizations. Competition between agencies for leadership roles and budgets can be debilitating. Integrating a program's budget and schedules through a much greater number of Congressional authorization and appropriation committees will be difficult. In addition, questions about the length and strength of commitment of new partners are a concern as are image considerations about nuclear and defense activities.

At this point this broad multiple agency approach appears to be the most viable option. Despite potential problems, most similar programs in the past have worked, and most space managers feel that if given the opportunity, this one will also.

Managing SEI can easily be the greatest challenge of the program, especially with multiple agencies taking major roles. Recent problems in managing large technical undertakings can multiply with more agencies, more laboratories, more contractors and sub-contractors, more advisory groups, and more committees. To succeed, the program must seek a straight forward organizational structure, strong leadership, confidence of oversight groups to allow flexibility, and as simple a budget process as possible.

Alternatives for managing the program are many. Traditional and modified management structures with NASA can be used if institutional reforms for a competitive, flexible personnel system, more flexible procurement procedures, and predictable, multi-year funding are adopted. A NASA lead organization can be led by an Associate Administrator for Exploration, or a super program office (above others at NASA), or rely on strong a strong lead center in the field. More innovative management structures include a board of directors from all agencies, a multi-agency skunk works, a hybrid national program office, or entirely new organizations such as satellite or JPL-like organization that might report to one of the above organizations.

Regardless of what options are finally taken, nearly everyone agrees that the program will need an extremely strong leader, a technically expert and innovative staff, and the confidence of the President, Congress and American people.

While NASA continues efforts to make programs work, a long line of problems in the Hubble, Space Station, and Shuttle stir up more criticism. In addition, the National Space Council may change the nature of the organization of civilian space. Finally, the Stafford synthesis group and Augustine review team are highly visible "blue ribbon" panels preparing recommendations that may very well set the country's space agenda and national organization for space over the next three decades.

As the momentum for change grows, Congress needs to closely oversee preliminary activities related to SEI and the future of the American space program. Although the initiative may be years in getting off the ground, it could be a catalyst for reorganizing our assets for civilian and defense space activities. Congress should stay well-informed on SEI issues such as the future roles of NASA, DOD, and DOE, and potential management alternatives for the vast technical program.

The purpose of this paper is to discuss SEI activities, identify issues of multiple agency participation and program management, and provide information for weighing issues and setting policy. The first section reviews current activities including the outreach and synthesis reviews. The second section considers partnerships for SEI and includes information on the perspective roles of the DOD and primary DOE laws. The third section reviews issues and alternatives for managing a very large space program implemented by a number of agencies.

The Space Exploration Initiative is bringing the American civilian space program to a crossroads. Its breadth and requirements demand reconsideration of the organization of our national capabilities. That, combined with persistent problems in current NASA programs, is creating an environment primed for change.

While NASA continues efforts to make programs work, a long line of problems in Hubble, Space Station, and Shuttle stir up more criticism. In addition, the National Space Council may change the nauture of the organization of civilian space. Finally, the Stafford synthesis group and Augustine review team are highly visible "blue ribbon" panels preparing recommendations that may very well set the country's space agenda and national organization for space over the next three decades.

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Current SEI Activities

Due to the initial zeroing out of funds for the SEI new start by the House and Senate Appropriations Committees, the program seems headed for a still birth at least for FY 1991. Nevertheless, a core of interest and excitement has enabled the momentum to continue.

In part the momentum has continued due to a degree of controversy over architectures, technical approaches, and NASA's capabilities. The outreach and synthesis activities have provided some press exposure and kept SEI in the trade journals. The Augustine review of the future of the U.S. space program and related NASA issues will provide new directions. Potential defense and nuclear weapons reductions are providing impetus to DOE and DOD to actively seek new directions. And, nearly the entire space community is "actively" waiting to see if adequate political support and funding can be obtained to make this dream more of a reality.

Outreach

The outreach program undertaken by NASA at the National Space Council's (NSC) request is receiving input from its broad based solicitation for SEI ideas. The program is apparently based on an AIA plan and an SDI effort and designed to gather ideas from a wide variety of sources through three primary channels. The RAND Corporation is analyzing ideas from industry, universities, associations and the public. The American Institute of Aeronautics and Astronautics (AIAA) is soliciting input from its members and Federal agencies are providing direct input to the Synthesis Group. Parallel to this effort, NASA is continuing its efforts with supporting contractor studies.

According to NASA in late August, the response to the solicitation for ideas has been strong, with RAND receiving over 1600 responses following 10,000+ requests for response packets. The AIAA received more than 500 ideas from its members. NASA, DOD, and several DOE laboratories are assessing and defining promising technologies, and are expected to present their findings to the Synthesis Group. Joe Shea, at a NASA advisory group meeting said, "this process won't come up with anything earth shattering...maybe a nugget or two."

In early September AIAA and NASA sponsored a technical conference to review the findings of AIAA's analysis teams. The effort was to uncover innovative strategies and technologies, but as Gordon Woodcock of Boeing's future programs office and several others admitted, "they did not find any 'magic bullets.'" In addition, leaders of technology teams reported they did not receive many new ideas. With the growing emphasis on a quick program, AIAA recommended a faster schedule, to the moon in 1999 and to Mars in 2009.

Although AIAA concepts did not use Space Station Freedom in early missions, a number of speakers made the point that it would be needed in the long-term. However, A recent article in Aviation Week and Space Technology described recent outreach program moves identifying concepts that avoid use of the Space Station Freedom. At the conference, Tom Stafford, said, "I know when I went to the Moon and back on Apollo 10, I did not have to stop at a space station."

The biggest question remains whether any truly "new" strategies or technologies that can revolutionize SEI concepts will be uncovered. The answer to this question may not be answered until the synthesis group completes its work.

Synthesis Group

Lt. General Tom Stafford, USAF (Ret.) is chairing a group of 22 senior space managers and 35-40 technical experts synthesizing input from all sources. Stafford has said that the group has the overall responsibility from the administration to blend and focus SEI technical alternatives. By February, 1991, the group will provide at least two, or up to six or seven alternative architectures, in addition to technology development priorities and near term priorities to the NASA administrator and then the National Space Council. They are also identifying and structuring rationales for the program. According to Stafford, his group is looking at management issues, in part because the Augustine committee will be providing recommendations in this area. Stafford said major goals are to make SEI as simple as possible, as light as possible and as quick as possible.

Currently, the synthesis group, organized into teams, is receiving a series of tutorials from industry, NASA, DOD, DOE and others about the possible requirements and technologies for the initiative. The DOD and DOE will probably present their assessments of NASA's 90 day study. According to a senior JSC official, NASA's centers are providing very limited systems analysis work to the group as requested by General Stafford.

Stafford has two deputies, Lt. Gen. Armstrong (Ret.) and George Abbey of NASA and a prestigious senior review group of Lt. Gen. Cromer, John McLucas, Pete Aldridge, and many others. Synthesis staff come mainly from agencies other than NASA; apparently only one NASA technical employee is involved other than George Abbey. DOD has sent about seven people, with five from Air Force, and one or two from Navy and Army. Several have come from SDIO. The Department of Energy has sent approximately individuals, mainly from the three multi-purpose labs. The Departments of Commerce and Transportation have no participants despite their standing on the National Space Council. Apparently, several contractors, Martin-Marietta and Rockwell International, have sent representatives.

"Stafford's challenge is to be independent," according to Jim Frelk of the Marshall Institute. This is a concern of many, including some at NASA. According to several team members, Stafford and his deputy Armstrong have "planted flags of independence" from both NASA and the NSC. Although both organizations are kept well informed of activities, most participants are confident the activity is independent. There also appears to be ample communication between Stafford and Augustine concerning overlap of their respective tasks. An initial interest in management issues in synthesis is declining as the Augustine group takes on the area.

Some involved think that Stafford might tackle the issue of whether NASA is the right organization for leading SEI. They say that the interim report at the end of October will provide important feedback from the NSC and NASA to re-focus efforts. The overall outreach/synthesis process is described by some as a "NASA credibility test."

Augustine Advisory Committee on the Future of the U.S. Space Program

Following the series of problems in NASA programs, the Bush administration appointed an independent advisory committee led by Norman Augustine to "advise the NASA administrator on overall approaches NASA management can use to implement the U.S. space program for the coming decades." Expectation is growing that the committee will recommend major changes to the management of civilian space.

The committee, comprised of long-term space experts and managers, science representatives, and two previous congressmen, Edward Boland and Don Fuqua, has a broad charter. Primary is the review of the future of the civil space program, including both management issues and program content. They will also assess alternative approaches and make recommendations for implementing future civil space goals. This second task has sub-parts including possible contributions by other government agencies, adequacy of overall skill base of work force, organizational balance and structure, balance between roles of government and private sector, and need to maintain a strong R&D capability, all important to other issues of this report. Recommendation on each of these issues will have great impact on a lunar/Mars program.

The first two and a half days of meetings provided evidence of directions the committee may take. NASA Headquarters management provided the first briefings after initial talks from Augustine and Mark Albrech of the National Space Council. The committee's interests follow the tasks described above, but specific questions and discussion provide evidence on their primary concerns:

1. Concern about organization of the agency, overlap of centers' roles and missions (as in Space Station), very complex program interfaces (as in Station and Shuttle), and a "tilt" toward continued too much power at the centers.
2. Need for more adequate cost and schedule margins in programs was described by NASA and heartily agreed to by committee.
3. Systemic budget fluctuations were discussed often, with questions about who caused them. They generally agreed all in the system, including NASA, OMB, and Congress, had some fault.
4. Very much concern about personnel issues, especially recruitment and retention due to low salaries and inflexible systems, there was concern about too few senior managers from outside the agency.
5. NASA emphasized and several committee members worried about the increasing numbers of support service contractors versus civil servants, and negative effects on maintaining high quality work force.
6. Committee members were concerned that NASA was getting "too much on its plate," and that the agency needed to give up something in order to take on more. There was a fairly contentious discussion between Truly/Thompson and some of the committee over the possibility of "spinning off" the shuttle to a contractor for operations.
7. The committee was interested in NASA having a high level independent assessment office.
8. NASA complained about (and the committee agreed) problems in federal procurement practices, including too lengthy of a process and inflexible procedures forcing to take the lowest bidder.

Admiral Truly's briefing to the Committee emphasized a number of NASA concerns:

1. Need to increase the experience and expertise base and develop leading edge technologies.
2. Must assure access to space by building OV-106 and developing a heavy lift capability.

3. Improve understanding of the need for and use of Space Station Freedom.
4. Must attain budgetary and human resources to match the growth in programs, and improve the civil service to contractor mix.
5. Need better compensation and benefits for human resources, fewer fiscal limitations, and less complex, time consuming procurement procedures.

A second set of meetings will have briefings from each of the NASA Center Directors and round table discussions on the first day and a second day with briefings from Gen. Tom Stafford, Gen. Donald Cromer, Dr. Lowell Wood, Dr. Lew Allen, Buzz Aldrin, and Dr. John Logsdon.

Administration

As noted above, the administration has initiated a number of activities that have a bearing on SEI, including establishing the Augustine Committee. SEI was announced as a major goal of the Administration in the President's July 1989 speech on the twentieth anniversary of the first lunar landing.

In a program with multiple partners, the National Space Council may acquire a stronger role seeking to improve management activities in SEI. If NASA's leadership role is decreased, a more decentralized program will need some higher level organization for a degree of coordination. However, this kind of organization can easily begin to slip into program implementation rather than policy coordination. Nearly every person interviewed (including senior managers at DOD, DOE, and NASA) expressed concern about the National Space Council potentially becoming overly involved in implementing the program.

Congress

The budget situation is the main issue for SEI in Congress. Until the White House and Congress can come to some terms on reducing the deficit it is unlikely that Congress will support starting a program with potentially very high costs.

There is very little support for starting SEI in FY 1991, except for the House Committee on Science, Space and Technology, where full funding has been authorized for the Initiative. The House Appropriations Committee zeroed out specific 1991 funds for mission studies for SEI, while the Senate Appropriations Committee severely cut SEI appropriations. NASA hopes for help from the Senate, but with the barrage of recent problems, little support is forthcoming. In June, Senator Albert Gore said, "I think the President needs a mission to reality," after an SEI kickoff meeting at the White House.

Partners for SEI

The Space Exploration Initiative will require the commitment of broad national resources and capabilities. The program's policy as detailed by the National Space Council calls for a partnership between NASA, the Department of Energy, and the Department of Defense. While this kind of arrangement has apparent advantages, a multi-agency program will bring special challenges that should be considered as the program is being framed.

Despite some concerns about NASA's technical and management capabilities, the president and National Space Council have determined that NASA will be in charge of the overall effort. However, with the Stafford synthesis group considering overall mission concepts and the Augustine committee reviewing current/future programs and management issues, this role is subject to change. The Department of Energy could possibly be a major player in the program because of its laboratories' technological capabilities and the expected decreases in spending for nuclear weapons. The Department of Defense, as the third partner, has much to offer particularly in transportation/launch systems, systems engineering, and acquisition expertise. A review by the Federal Laboratory Consortium identified 42 DOD labs and 17 DOE labs that have some capabilities that might be applied to SEI. Clearly the agencies have considerable capability to offer.

A major reason to involve other agencies is to invigorate the overall effort. NASA's 90 Day Study was seen by many as an unimaginative effort by an aging bureaucracy. A member of the Marshall Institute quoted a report by a NASA employee on bureaucratic problems in the agency. He also described "institutional bloat" and identified the "not invented here" syndrome at NASA; as in fact did some senior NASA managers. New blood involved in the space program might re-invigorate NASA.

Technical capabilities and potentially key technological contributions lead the list of advantages of DOE and DOD participation. A division of labor will allow each agency to specialize on traditional areas of expertise, build on core strengths, and increase capabilities. Healthy competition between the agencies should foster greater innovation and technical competition of technical ideas, in addition to revitalizing NASA by providing broader consideration of approaches. Costs of the initiative will be spread across a number of agencies thereby providing a broader budget base. Involvement of more agencies might increase political support as supporters of other agencies see benefits. The CBO report on "NASA in the 1990's and Beyond" provides the example of DOD cooperation on space transportation investment and operation to increase civil space effectiveness by avoiding duplication and increasing coordination. Moreover, if defense reductions continue, increased efforts involving SEI can offset reductions and maintain or improve the labs' strengths.

There are nevertheless serious disadvantages that make the multiple agency approach less appealing than it first appears. Effective management of the program becomes a primary concern as more participants become involved. Complex technical interfaces can become more difficult when governed by complex management interfaces and dispersed responsibility, as evidenced by the Space Station Program. This is contrary to the simple, direct, and straight forward program management recommended by nearly everyone interviewed. Extreme competition or conflict between the agencies can disrupt and cripple programs. Authorization and appropriation for the initiative may be more difficult due to the numerous Congressional committees and sub-committees involved. Difficulty implementing major programs efficiently due to vacillating budget figures will be exacerbated by budgetary integration requirements for a long term, highly interactive program.

Other potential problems are less obvious but possibly equally important. DOE and DOD carry image baggage that NASA has avoided to fair degree in the past. DOE has a "nuclear" image and weapons reputation due to past/current activities and its core capabilities. As seen with Shuttle missions with RTG's, nuclear components can stir up negative publicity. Nuclear weapons labs deeply involved in civilian space may have some negative consequences. DOD's activities in space defense and nuclear weapons can also tarnish NASA's generally civilian image.

Independent elements of independent agencies may prove to be quite difficult to manage on the long-term and in specific situations. Just as NASA centers can turn to their political/contractor/public constituencies to influence program or technical decisions; DOE, DOD, and NASA have influential advocates. Program definition, design, and development could become quite protracted in the inevitable disagreements.

The permanence of each agency's participation is another concern. Current interest is great, but will it remain if the geopolitical order abruptly changes and great increases in defense weaponry are again required? The suddenness of the Middle East crisis and the U.S. military buildup emphasize the risk of sudden priority changes by space partners.

Space professionals have mixed opinions concerning the value of multiple agencies playing major roles. Most expressed confidence that multiple agency programs could work based on past successful collaboration. Pre-Apollo, Apollo, and on-going work are often cited as evidence of positive working relationships. Arnold Levine, in Managing NASA in the Apollo Era, wrote, "Perhaps the most remarkable thing about the NASA-DOD relationship is not that it worked so well, but that so often practice was better than theory~~,~~ and mutual interest overrode the funding and duplication controversies..." On the other hand, some of the same people point to NASP and ALS for examples of potential problems. Typically the problems occur because of an organization's changing priorities. Some problems, such as past disagreements on funding arrangements between DOD and NASA for NASA launches at the Eastern Test Range and current disagreements over funding for DOD range support identify the type of issues that can trouble relationships for years.

Space managers were concerned about management authority over parts of the program and competition between organizations. A current NASA program manager, at first thought there would be major problems managing and directing activities across agencies. But, he felt that

"Apollo-like" clean interfaces and clear roles and responsibilities such as "DOD, meet us at the launch pad with an HLV with these capabilities," could make partnerships successful. A past NASA manager of many programs thought SEI was similar in some ways to Apollo which he described as a multiple agency program with "fairly easy" integration.

NASA

Despite current problems in other programs and SEI budget difficulties, NASA continues working on SEI. With the president vocally supporting the initiative and increasing NASA budget requests, NASA sees the program as a potential integrating force for the agency's future. There are no signs that NASA plans to give up on this program.

NASA continues its primary role in spite of the multiple reviews ongoing. The agency organized the outreach program and playing a coordination role for SEI activities at the edges of the Synthesis Group. NASA is also developing mission plans and technology studies (using DOE for support) for its own submission to the synthesis activity. NASA has done substantial technology and mission architecture studies since the original 90 day study.

NASA's 90 day study was probably the pivotal issue of SEI over the last year. Although some at NASA complain that they weren't given adequate task definition from the NSC, the study's conservative approach has been used by critics as evidence of the agency's lack of innovation. While the agency may lack innovation to a degree, the 90 day study wasn't a blueprint for a specific mission and shouldn't be criticized as such.

The Office of Exploration at Headquarters currently has a staff of about 25 working on technical issues, policy issues, external relations, coordination within NASA and with other agencies, budgets, and managing the outreach effort. A level two, Lunar Mars Exploration Office with a staff of about 22 has been established at the Johnson Space Center, while level three offices are being organized at other NASA centers and possibly DOE labs.

Department of Energy

DOE's laboratories offer technical expertise in nuclear power, nuclear propulsion, and radiation protection all of which may be key to a more viable program. The labs also have broad experience in a variety of technical programs and technical integration. The labs are more R&D oriented than the NASA centers, which over the years have been growing more operations oriented.

According to Hans Mark, in his book, The Management of Research Institutions, Edward Teller felt that to spawn new technologies an element of internal competition within the government/contractor community would be important. Lawrence Livermore National Lab was, therefore, spun off of Los Alamos, and the competition between the labs has been quite successful. The labs enjoy a strong reputation for high quality, innovative technical work.

DOE has yet to name a "space czar" to coordinate agency-wide SEI and civilian space activities, although the Secretary's office is focusing agency-wide activities. Recently in late August, DOE Headquarters sponsored meetings to review current SEI activities at the labs.

Since the House Appropriations Committee voted to reduce the funds, the DOE approach to SEI work has been guarded. In a Senate hearing on the evolving roles and missions of the laboratories, Senator Domenici told the lab directors en masse that they'd better approach new fields of work with care. In this hearing space related work was barely mentioned by the labs and SEI was not mentioned by anyone, despite considerable activity at the labs. DOE Headquarters has been working to bring more control to the activities of the labs as they begin to work in less traditional areas.

Review of Labs

Lawrence Livermore, Sandia, and Los Alamos, the multi-purpose and larger DOE labs are very interested in moving into civilian space in general and SEI in particular. They strongly expect nuclear weapons programs to be reduced and expect space activities can fill the gap.

The laboratories are taking independent routes toward increased space work, marked most obviously by Lowell Wood's continued promotion of "Great Exploration", the NASA/DOE MOU and National Space Council policy calls for DOE support on both technology development and innovative approaches to missions. With Sandia and Los Alamos emphasizing technology development and Lawrence Livermore focused on mission strategies, both major tasks are covered by the DOE.

Lawrence Livermore National Laboratory (LLNL)

SEI activities at Lawrence Livermore are centered around Lowell Wood and his Great Exploration program. Despite persistent attempts and repeated questions, the personnel there could not or would not identify anyone else involved in SEI or activities potentially related to SEI. As of August, LLNL had not reviewed current technological capabilities in reference to possible application to SEI, but focused only on architecture.

There is no current organization at LLNL for space related work. Lowell Wood is the only identified point person for SEI activities. And, he and three or four support people provide the focus for SEI related work.

As of mid-August, activities did not include exchange visits o workshops with NASA, identified by DOE headquarters and other labs a important initial steps. According to Wood, LLNL plans to send one or two people to work on the Stafford synthesis activity. LLNL personnel said there is no plan for approaching SEI activities and that no budget figures have been identified at the lab. Wood said they were waiting for the DOE/NASA MOU to be signed and some budget authority before moving forward.

As of mid-August, LLNL had not done a skills and technologies inventory related to SEI. Several areas of lab expertise potentially useful for space work included mathematical modeling of physical phenomenon, computational capabilities, materials research, planetary geology, and innovative approaches to technical problems.

Current work for NASA (not specifically tied to SEI) is comprised of 14 projects totaling about $430K. Work is diverse including a review of Shuttle main propulsion, LDEF analysis, theory of aerobraking, soft x-ray background and geology and geophysics. LLNL expects considerably more in the coming year, with large programs such as UARS theoretical investigations, 2-D modeling of aircraft global impacts and spectroscopic investigations potentially increasing funding by nearly $4M.

Of the 8,247 FTE's at LLNL, approximately four thousand work in nuclear weapon research, development, and testing, while two thousand work "for others" on various projects, and the final two thousand are split in descending order among laser isotope separation, laser fusion, magnetic fusion, energy, biomedical research. "Work for others" has grown steadily since 1972, nearly doubling since 1983. Nuclear weapon RD&T peaked in 1987 and has dropped about 400 since then.

LLNL's Institutional Plan for 1989-1994 contains the lab's strategic view as of 1989. At that time no major changes were expected in the distribution of resources among major programs. However, LLNL did not expect near-term budgets to keep pace with inflation, reflected in their budget plans with a 440 FTE decrease between 1991 and 1994. Not only did nuclear weapon RD&T decline by 1990, but the lab expected further general decreases through 1994. Weapons work had leveled off and appeared to be trending down before the changed geopolitical climate of 1989-90. The expected large reductions in the future will require LLNL to identify new work. Civilian space is a field that LLNL probably needs.

Sandia National Laboratory (SNL)

Sandia is excited about the prospect of becoming more involved in civilian space. SNL's Director for Laboratory Development and those involved in space related work are identifying and marketing their capabilities to increase involvement in space as nuclear weapons work declines. And, they do expect nuclear weapons work to "drop drastically."

SNL staff wanted to ensure that Congress understands how different they were from other labs. They feel SNL is more accountable than the other labs because their work is more product oriented. They do more systems engineering and integration to build satellites, build technical hardware and generally develop products.

John Bertin is the identified lead for SEI at the lab and has been working closely with both NASA Headquarters and various NASA centers. SNL has specific objectives and activities to be a "cooperative partner" on SEI with private industry, NASA centers, DOD labs, and other DOE labs. According to one briefer, "SNL can provide nuclear space technology to DOD and NASA just as it provides nuclear space weapons technology to DOD."

SNL has developed strategic plans for approaching SEI work. The lab wants to develop its image as a technical force by marketing its mature technology bases including nuclear activities (propulsion, power beaming, and surface nuclear power), flight test (support to NASP/Shuttle derivatives, instrumentation, hypersonic technology, and computational fluid dynamics), and hypervelocity impact (space debris). Exchange visits with NASA JSC, NASA MSFC, and Boeing are underway to coordinate activities. SNL personnel are taking active roles with NASA and DOE committees to develop SNL's image as planner and role as a decision maker in the program.

John Bertin and Bob Clem of SNL are going to be representatives to the Stafford synthesis activity. SNL will also provide support to Stafford in the area of nuclear technology for space.

SNL has a broad nuclear technology base that can support SEI. In fact, SNL feels it has important capabilities for four of the 7 critical technologies identified in the 90 day study (advanced space engine, surface nuclear power, radiation protection, and nuclear thermal rocket propulsion).

SNL wants to focus on beamed power, nuclear propulsion, and robotic systems. Low power lasers can power beam long term power requirements for space station and lunar stations. SNL has briefed NASA on nuclear space power and power beaming and fall workshops are planned with JSC, LaRC, LeRC. They expect their technologies to be an important part of SEI. SNL, working closely with LeRC and MSFC on nuclear propulsion systems, is a member of a joint NASA/DOD/DOE steering committee, is participating on nuclear electric propulsion and nuclear thermal propulsion workshops, and is providing six SNL staff for SEI technology review panels. SNL staff believes their nuclear technologies capabilities are critical for more efficient systems to reach and colonize the moon and Mars.

Sandia's budget for FY89 was $1.167B with approximately 58% for defense programs, about two percent for conservation and renewable energy, two percent for civilian radioactive waste management, and nearly two percent for energy research. In 1989 approximately 30% of SNL's budget came from federal agency reimbursibles, with 301.7M from DOD, 22M from Nuclear Regulatory Commission, and 58.4M from other federal agencies.

The FY89 - FY94 Institutional Plan offers only a general paragraph about NASA and ESA work and never mentions the SEI program. The Institutional Plan (obviously overtaken by recent events) shows through FY94 a four percent increase in FTE's for DOE programs, about a 27% increase for DOD programs, and a 15% increase in FTE's for other agency work. The FY94 total would be 172 of the lab's 8450 FTE's, and NASA related work would be a small subset of the 172. Of course the institutional plan was developed prior to budget factors of "peace breaking out," serious consideration of SEI, and expansive defense actions in the middle east.

SNL officials refused to attempt to predict future budget figures. However, they felt strongly that SNL faced large decreases in nuclear weapons work that needed to be balanced by increases in other areas, and SEI was a preferred option.

Los Alamos National Laboratory (LANL)

For Los Alamos, as Sandia, the SEI program is an important new mission to replace decreases in nuclear weapons work. LANL is moving out on SEI, actively working with both DOE Headquarters and NASA Headquarters and field centers. In SEI related work, this lab is the most organized and active. LANL officials want to ensure that we understood their space related technologies and capabilities and their long-term experience in space activities.

Similar to SNL, Los Alamos is working within DOE's plans and the evolving NASA/DOE framework. Richard Burick is assigned SEI Program Manager to coordinate internal LANL efforts and external interfaces. LANL officials identified nuclear thermal propulsion, nuclear electric propulsion, surface/space nuclear power, radiation protection, in situ resource utilization, advanced materials, energy storage and transportation, biological effects, supercomputing, and advanced diagnostics as critical SEI technologies in which the lab has considerable expertise.

LANL efforts are in nuclear thermal propulsion, nuclear electric propulsion, and space/surface nuclear power, followed by materials research, hypervelocity impact research, radiation protection, and in situ resource utilization. Although LANL officials said DOE HQ was somewhat disappointed in the slow speed of the labs' SEI involvement, in nuclear power and propulsion LANL has coordinated a number of meetings, workshops and studies with NASA. LeRC, Idaho, and LANL are currently teaming on nuclear propulsion initiatives; and Lewis has proposed that LANL and Idaho serve as level 3 project organizations with Lewis Research Center as the level 2 program office. Within Los Alamos, disciplinary and inter-disciplinary working groups are analyzing SEI requirements.

LANL is actively promoting nuclear propulsion as a key technology for SEI because of potential savings in mass to LEO and reduction in trip time from 3 years to less than 1 year. Los Alamos, with many years experience in nuclear thermal propulsion, has considerable expertise in design, development and testing of Rover/Nerva technology. They also recommend nuclear electric propulsion for robotic and cargo missions.

LANL's Theoretical Division is working on space radiation hazards to better identify hazards and requirements for protection. Here, as in the above technologies, the lab has in-depth, long-term experience in closely related multi-disciplinary work particularly well suited for heavy ion measurements, theoretical model development, particle transport code application, satellite measurement, biological effects research, and radiation shield design involved in assessing space radiation effects and protection. They predict that reducing the large uncertainties in shielding requirements will significantly reduce mass margins for Mars and lunar expeditions.

LANL is also promoting dual mode nuclear power. Dr. Steve Howe has briefed most parties involved including the National Space Council, NASA, etc, about dual mode advantages. He predicts a factor of 2 to 3 reduction in ship mass in LEO versus chemical systems, a potential 1 year round trip Mars mission, and high grade electrical power for a lunar base. According to Howe, NASA is very interested in this technology. Los Alamos also offers the Sp-100 program as an attractive alternative for space and surface nuclear power.

The lab has a long-term focus on space related work. Of the labs, only Los Alamos has an established organization for space sciences where SEI work is coordinated. The lab feels that it has valuable experience in integrated space projects with such organizations as NASA, DOD, ESA, and the Federal Republic of Germany.

Responding to a request from the National Space Council, LANL staff in January 1990, developed a critique of NASA's 90 day study based on questions provided by the Council. According to the critique, "the NASA study relies on existing or easily extrapolated technologies for its baseline approaches and does not take credit for new technology development." The report describes how the program should be organized to aggressively force technology development, how the DOE labs could be used to force it, and then how traditional DOE technologies can provide the innovations needed. Questioned about innovative uses of existing technologies possibly overlooked, the report offers 1. nuclear thermal rockets based on Rover technology, nuclear power from dynamic isotope power systems, 2. small nuclear reactor systems, and medium nuclear power systems, 3. radiation protection based on the DOE's many years of practical experience, and 4. a number of strategies for development of resources in space.

The LANL critique questioned the following NASA assumptions; 1. requirement for and definition of unmanned precursor missions, 2. that the HLLV will be adequate and ready on time, 3. that Space Station Freedom will adequately support the mission, or whether a separate service station should be considered from the outset, 4. the need for artificial gravity, and the availability of adequate radiation protection and life support systems. The report said costs of several $100 billion are not unreasonable when spread over 30 years. At this point the criticisms seem rather obvious, but in January they probably helped set the agenda.

The laboratory has diverse technologies and capabilities that can fill gaps in NASA's capabilities for potentially important options for mission requirements. LANL staff is excited about working on the challenges of the SEI program. Los Alamos officials see non-defense R&D as critical to the vitality of the laboratory. Space related work and work with NASA are seen as important evolutionary roles for the lab.

NASA funded research at LANL has grown steadily since FY86, from $2.88M to an estimated $5.8M in FY90. Research areas that presently receive significant support from NASA include atmospheric and ionospheric physics, space plasma physics, space astronomy and astrophysics, planetary science, materials science, and NASP studies.

In 1990, about 4200 of the 7800 lab's FTEs are committed to DOE/Defense programs, with about 1800 involved in DOE energy and research, and another 1800 working for other programs. Work on defense programs has dropped about 400 FTE's since 1983, while DOE energy and research has stayed varied little since 1980. Work for other programs has grown considerably since 1972 and in fact this work doubled between 1983 and 1985. Much of this increase was due to DOD increases in SDI and advanced conventional munitions.

The FY90 budget has about 53% DOE/defense programs, 22% DOE energy and research, 22% DOD, and 3% reimbursibles for other agencies including the Nuclear Regulatory Commission, National Institutes of Health, and NASA. When asked to identify or predict budget plans for years beyond FY 90, LANL officials said details were too unclear to make any predictions or identify specifics.

DOE labs in general

Technical personnel at each of the labs said they preferred working with NASA on technical projects to working with DOE. They said that there was less bureaucracy and quicker turnaround on project budgets and administration. Generally, laboratory relations with NASA were characterized as very good to excellent. Agency relationships seemed quite good at the field level, while in Washington the relationships are marked by caution.

The DOE labs' technical capabilities fill surprisingly well the open areas of NASA's capabilities in a number of technologies identified as critical to a lunar/Mars program. Nuclear power, nuclear propulsion, radiation protection expertise are significant.

Department of Defense

DOD has approached SEI in a more deliberate manner than DOE. This may be because DOD has ongoing activities more readily adapted to SEI, whereas DOE is evolving toward in new missions. According to DOD staff, the agency wants a strong role, but doesn't want to get out in front of the plan.

DOD has taken a more centralized, "top down" approach beginning with a blue ribbon panel, chaired by Gen. Cromer, that reviewed NASA's 90 day study, proposed how best to do a lunar/Mars program, and analyzed reasons for doing the program.

The panel, comprised of highly experienced space managers including Augustine, Abrahamson, Aldridge, and Shriever, studied how best to implement a lunar/Mars program, which included suggestions to use SDIO as a management model, have a single budget for the program (rather than through separate agencies and committees), shorten the program for more near-term payoffs, and use a reformed NASA as the program lead.

While discussing rationales, an Air Force official provided insight on why DOD seeks SEI involvement. He mentioned the changing geopolitical environment creating a need within the Federal government to work closer together in mutual, interdependent efforts (thus avoiding program overlap). He cited the increased competition for declining budgets leading to a need to transfer current aerospace work in broader areas such as SEI. Maintenance of DOD's technical infrastructure and capability, as well as that of its contractors and sub-contractors was identified as an important reason to proceed with SEI

According to Pentagon lab management personnel, the DOD labs, smaller and more dispersed than DOE's, have been taking a wait and see approach to the initiative. As of late July, they had not begun to look at SEI or determine approaches to its requirements. He identified some labs with likely applications; Space and Missiles (astronautics) at Edwards, for liquid and solid propulsion, space structures, materials, orbital transfer vehicles, and space power; Materials Lab at Wright Patterson for composites and carbon work; and the Space Technology Center at Kirkland for radiation hardening. He expected the Air Force Systems Division to seek systems integration and program management roles. The lab managers reported that they have historically had good working relationships with NASA at the field level.

Colonel John Otten, in Space News, described the U.S. Weapons Laboratory at Kirkland Air Force Base as in transition. With expectations of a decreasing defense budget, the lab is increasing concentration on space assets. Although Otten downplayed radiation resistant electronics applications for exploration, he said the lab could work on payloads and optical work. Otten described the Air Force's interest in the lab's performing more exploratory development and basic research. They also want to improve their in-house capability and decrease their reliance on contractors to run big projects. Evidently, the DOD labs have a number of similar issues as the DOE labs and NASA.

Currently, there are no dedicated SEI personnel in the labs. However, now that the DOD task force is set up, the labs are expected to become more involved, as evidenced by their providing about half of DOD's support to the synthesis group.

In mid-August DOD assembled an SEI task force, chaired by Dr. Gene Sevin, to begin coordinating agency-wide SEI activities. A support staff of up to 40-50 (on a part-time basis) split into panels to develop input to the Stafford synthesis activity. Synthesis input, a first task, includes four goals: 1. to survey DOD for existing technology developments and capabilities, 2. to status the availability of technology capabilities and developments, 3. to identify innovative ideas applicable to SEI, and 4. to provide "sustainability" recommendations concerning maintainability, logistics, etc. In addition the task force is divided into management, systems and architecture, transportation, and technology panels heavily weighted toward transportation considerations. Air Force agencies are being matrixed into the four areas to support the task force.

Of the services, the Air Force has clearly taken the lead and seeks the SEI lead role within DOD. The Air Force has identified "equities" to support SEI and to be supported SEI for future Air Force requirements. According to Air Force personnel, expertise in the following systems may make major contributions to SEI:

- reliable/low cost launch systems, large/heavy lift launch systems, upper stage launch systems, advanced systems such as NASP, and launch systems operations
- electric, nuclear, and solar sail propulsion
- solar cell and reactor space power
- launch/range/satellite control infrastructure
- transportation systems logistics
- acquisition expertise
- and a variety of technologies

Management of the Space Exploration Initiative

Management of multiple agencies performing highly complex interrelated work may be the most daunting challenge of the Space Exploration Initiative. Some current and past NASA managers say that over concentration on technical issues may be a mistake when management issues can have equally critical results. Experiences with the Hubble Space Telescope, Space Station, and Space Shuttle programs dramatize problems of schedule slippage, simple mistakes on complex equipment, and extreme cost run-ups caused or associated with program management problems. Since SEI's size and scope will challenge the limits of even the best program management, a much greater emphasis is required.

One previous program manager, said SEI should be seen as a "flight project," to not be overwhelmed, but "underwhelmed" by its challenges. He said further, "Don't set out to develop a huge program, because what you'll get is a huge bureaucracy."

The challenges of program management include leading and coordinating three or more agencies, managing budgets and program phases through a greater number of congressional committees and executive organizations, directing and overseeing contractor activities, and providing policy and political leadership. Hopefully, both the Stafford synthesis activity and the Augustine review board are closely examining these issues to identify effective solutions. Various options for managing the program need to be carefully reviewed by both Congress and the administration before moving forward. And, Congress should look very closely at any program management decisions to ensure that new management structures offer real solutions, not change for change's sake.

Program leadership and management demand a solid lead organization with clear lines of authority and responsibility with partner organizations. The Aerospace Industries Association (AIA) SEI Task Force called for a strong focal point to lead the effort. A long-term NASA program manager and current Space Station contractor, felt a major complex technical project done by multiple agencies "cries for a solid backbone of management." The lead organization must have strong technical capability combined with presidential confidence to undergird program authority with partner organizations. Organization assignments must be distinct and specifically identified with each responsible party to ensure ownership and responsibility for results.

The lead organization must be strong in stature supported by a technically skilled staff. Nearly everyone interviewed felt that a strong management organization was needed to make management work. The DOD blue ribbon panel reported that the program manager had to have a strong staff with systems engineering expertise. A previous Apollo, Skylab, Shuttle, and Space Station manager said "during Apollo you had to have a strong lead center, you couldn't wait for consensus." A previous Shuttle program manager said strong management was required to force coordinated approach and that the lead agency must have great technical capability.

An important aspect of strength for a management organization is the ability to make decisions without excessive oversight. On the long-term, the bureaucracy surrounding such a complex program should be reduced. The managing organization needs adequate latitude to implement policy without excessive second guessing by reviewing organizations. The National Space Council, Congress, and possible multi-agency boards should limit their involvement to policy review and avoid continual explanation, re-phasing and rejustification. The ongoing GAO study concerning these issues should define some real costs associated with "overlayered" program review.

A strong thread of frustration due to "excessive" oversight ran through a number of discussions with public and private space program managers. Obviously this highlights a dilemma. When major problems in the programs occur, additional oversight is required. However, in, "Accountability in the Public Sector: Lessons from the Challenger Tragedy" Romzek and Dubnick wrote, "NASA needs to return to...a professional accountability based on deference to expertise...instead it faces increased environmental pressures calling for adoption of political, bureaucratic, and legal accountability mechanisms." In the 1960's NASA was the expert, it had faith in itself, and the faith of nearly all others, as one former NASA manager said, "the rest of the world left them alone." The challenge for future programs is to find that level of professional expertise that allows more complete concentration on technical problems and solutions.

Hans Mark in his book on managing research institutions, identified organizational flexibility as an element of success important to the new NASA of the 1960's. NASA had no long-range plan, no general advisory committee, no inspector-general, chief scientist or chief engineer, and no central planning staff for the Administrator. As a new "pre-bureaucratic" organization, NASA could avoid becoming captive to policies that might "cease to be relevant."

Clear lines of management will be difficult to define with many levels of agencies and contractors; and yet nearly everyone interviewed felt simplicity of management systems was a high priority. A senior member of NASA's Office of Exploration said to "keep management simple, simple, simple." SDI was mentioned by a number of people as a model for an SEI management entity because of its small size and great autonomy. Although some DOD lab managers felt the management of SDI "was a mess." They felt it was too small, centralized, and focused.

For reasons of simplicity, a straight forward pure project type of organizational structure would probably be best for a multiple agency program. See the attached chart from an article, "Managing R&D Projects," in the June 1988 Research Technology Management for a description of advantages/disadvantages of project versus matrix management organizations. For a program as large as SEI, project management's reduction of interfaces, unity of command and basic simplicity are preferred. A matrixed multiple agency organization has very high integration and communications costs. Several former and present NASA managers felt that the program had to be cleanly split into nearly self contained projects managed from a lead organization in order to succeed. For similar reasons, one manager felt that only one organization should be involved in program management, with each agency having considerable independence within program requirements.

A member of the original Space Task Group stated that SEI requires an extremely strong and large political base, which often leads to poor rather than good management. Program and hardware requirements must be defined with a sharper focus as in smaller programs. Attempting to be "all things to all people" by meeting a great multiplicity of requirements leads to designs of the "lowest common denominator." Finally, the lead organization must have authority over each participating organization's SEI work and must be located where a strong, supportive technical staff can be acquired.

The former Space Task Group member feels that management structure needs to fit the program, that highly interactive program pieces lead to highly interactive program management. SEI, unlike Space Station, may not need to be highly interactive. He said, "Break it into segments and decrease need for interaction." As did Jim Herrington of AIA, who feels that the program needs to be broken up into smaller projects.

Budget systems will have important effects on management success for SEI. Budgets that follow lines of program authority will help ensure that the managing organization has the greatest possible control and responsiveness from other organizations. Decentralized budgets can lead to excessive independence of participating organizations, misalignment of inter-related schedules, and very difficult program integration. Although a number of respondents (including DOD's blue ribbon panel) felt budgets should flow through NASA to the other organizations, representatives from NASA, DOD, and DOE report that current plans have each agency controlling its own funds. One Air Force manager said if the funding doesn't go through NASA there will be "mass confusion."

Program Management Alternatives

NASA is named lead agency under the administration's current policy and most parties agree that NASA should lead. The NRC said in its review of the 90 day study, "NASA has the organizational expertise and demonstrated capability to conduct human space exploration." In interviews, representatives of both DOD and DOE expressed confidence that NASA should and would provide SEI leadership. The DOD blue ribbon panel reported that a reformed NASA should lead the program. The members of Aerospace Industries Association (AIA) felt that only NASA had the experience to manage SEI. Despite concerns about it's capabilities, NASA or some derivative will probably play the lead role.

However, there are some options that may offer variations of a modified NASA or hybrid organization in control. Due to the recent problems, some type of a 'reform' may be required.

Institutional Reforms

Regardless of what organization manages the program (unless it is a GOCO type), some initial, low impact steps should be taken to improve the administrative processes involved in managing and procuring major space systems. These actions would help a NASA or other federal agency speed up programs, make them more consistent, and ensure availability of best possible technical expertise. The institutional environment must be improved.

Budget Process

First, the budget process can be smoothed by adopting multi-year funding to allow more long-term planning by the implementing agencies. The Packard Report recommended that Congress and the Office of Management and Budget authorize funding for R&D programs on a predictable multiyear basis so that staffing levels and activities can be properly planned. The CBO report, "The NASA Program in the 1990's and Beyond" argues for multiyear funding to provide less appropriations gaming and better planning efficiency, enhanced relations with international partners, and better understanding of overall program costs early in program. The Packard Commission also strongly endorsed predictable, multi-year funding to allow proper planning of research activities and personnel levels. Predictable funding will lead to more effective, cheaper programs in the long run.

Procurement System

The need to modify the procurement system to provide greater speed and flexibility for procurements was identified in a number of interviews. The Packard Report on federal laboratories recommends, "simplifying the necessary Federal procurement procedures...(and giving) laboratory directors greater flexibility in contracting." Government and contractor representatives complain bitterly about excessive "social" requirements and red tape. Alternatives range from adjusting current systems to make them less burdensome (often advanced by aerospace contractors) to Lowell Wood's recommendation to obtain generic waivers of procurement regulations as in "black programs." And greater accountability from contractors is becoming a requirement. If organizations are paid awards before the success of their work is known, we can expect more problems like Hubble. A workable combination must be found that balances independence and flexibility with accountability and responsibility to avoid the development of institutionalized procurement relationships similar to a "military/industrial" complex.

An ex-Shuttle Program Manager had strong opinions about the need for synergism between procurements. He feels the process needs to "modularize" from project to project.

Personnel Management

Personnel management is a third management area that can be reformed if the program remains in the civil service. Alternative systems offer greater flexibilities for pay, incentives and awards, recruitment, and managing to budgets rather than FTE's. The Packard Report recommended creation of, "a scientific/technical personnel system that is independent of current Civil Service personnel systems." The report also recommends that personnel ceilings should not be used in addition to budgetary control. Jim Herrington, of AIA, said "the compensation system has to be fixed or you won't have any type of program...you've got to have talent, otherwise you only have a very small contract monitoring staff." And, recently in the Augustine committee briefings NASA emphasized the importance of personnel "reforms" to enable greater technical expertise.

The inter-related issues of contract management by NASA employees and growing numbers of support service contractors dramatizes a need for more human resources for a growing space program. The squeeze on limited resources by growing programs results in NASA technical employees doing less "hands on" research and engineering, and more monitoring of technical contractors, inevitably leading to deteriorating skills and dated expertise. Werner Von Braun, in a 1965 House Authorization hearing said, "**A good engineer gets stale very fast if he doesn't keep his hands dirty....**it is for this reason that we are spending about 10 percent of our money in-house; it enables us to really talk competently about what we are doing. **This is the only way known to us to retain professional respect on the part of our contractors.**" In addition a "hands on" engineer, not diverted into contract management, is more likely to originate innovative ideas for tough technical challenges.

A 1989 NASA recruitment survey found widespread concern about excessive contracting out and contract monitoring tasks for civil servants. One recruit reported being told by several NASA contractor recruiters, "Why go to NASA, all they do is manage contracts, we do the real work." Changes need to occur to renew NASA's core technical capability. If NASA takes a large role in the project more civil servants will be required to enable more widespread "in-house", "hands-on" work.

If NASA continues to have the major leadership role in SEI, the agency will need to improve its technical capabilities to avoid mistakes such as Challenger, Hubble, and Space Station. State-of-the-art technical expertise of employees will improve program definition, contract management, and program management. To acquire and maintain skills, the agency must have a competitive pay system.

A Reorganized Agency

A possible "reform" that can be considered is a reorganization of NASA to better meet the challenges of the future program. Hans Mark, with broad experience in both NASA and DOE, identified the need for a clear separation of management of operational and developmental programs which he said was currently inextricably mixed at NASA. He felt there was too much overlap of centers' roles and missions.

Mark recommended reorganizing NASA by appointing separate AA's for Space Shuttle and Launch Vehicle Operations, Space Station Development, and the Lunar Mars Initiative. Mark would place shuttle operations, both launch and mission control, at Kennedy Space Center; responsibility for Space Station development at Johnson Space Center; responsibility for a lunar program to Goddard Space Flight Center, and the Mars program at JPL. While these specifics may be easily criticized, the possibility of cleaning up roles and missions of the centers should be considered. There already seems to be some interest by the Augustine committee in restructuring roles and missions of the centers.

Managing Organizations.

Considerations

Many proposals are being considered to manage SEI. Below are a few of those identified. This is not an all inclusive list, but these are likely options for a future program management decision. Confidence of the executive and legislative branches and the public is a bottom-line requirement for any managing organization to succeed.

In the 1950's and 1960's the U.S. military originated two systems development philosophies often cited as examples of highly successful development projects; the Air Force Western Development Division's ICBM program and Navy's Special Projects Office (SPO) Polaris Missile program. These examples should be considered in any assessment of potential management structures for future space efforts.

General Schriever shortened schedules and the Air Force delegated to civilian corporations every aspect of the R&D cycle. They hired Ramo Wooldridge (later TRW) as the technical director to provide systems engineering and long-range planning for the program. The Air Force created a technical capability outside the government to meet a major technical challenge.

Unlike the Air Force, the Navy provided technical direction for Polaris and relied on numerous contractors rather than one. The Navy Technical Director, therefore had the advantage of competing proposals in a highly decentralized organizational structure. The Marshall Institute report, New Directions in Space, cited the Polaris Steering Task Group, which reported to the Polaris program director, as an "independent" blue ribbon group (including some Navy unit chiefs) that contributed greatly to the Polaris success by acting as a board of directors. The SPO sought to co-op critics by soliciting their advice. Like Apollo, SPO had no outside advisory group that might slow the program by demanding certain projects. Also, like the 1960's NASA, SPO had a reputation for managerial effectiveness, which allowed SPO to maintain independent control of the Polaris program. Polaris was a success; it met all of its goals, stayed within cost, and was completed years ahead of schedule. Books by Harvey Sapolsky, The Polaris Systems Development, and Hans Mark, The Management of Research Institutions, provided most of the above material on the ICBM and Polaris programs.

A new organization has some natural advantages simply because of its newness. A new organization can quickly organize for new undertakings by bringing together experts from a variety of sources to build highly focused, productive teams. A new organization has less bureaucratic inertia, fewer feifdoms, and less growth of bureaucracy. Newly created organizations have been very successful in the past; NASA with Apollo, Los Alamos and the Manhattan Project, the Polaris Task Group. A new organization can quickly develop an esprit de corps and culture tightly focused on the specific goal, without resources diverting to other programs. Nevertheless, these considerations must be weighed against the value of mature organizations with experienced, refined capabilities.

Options

Associate Administrator for SEI

The most traditional option would be to simply re-establish the Office of Exploration at the Associate Administrator level in NASA. This is seen by some as "business as usual" and offers minimal disruption. Providing significant visibility and authority are obvious advantages. Initiatives would have to be undertaken to fix many of the impediments that hound NASA; civil service personnel system, federal procurement system, etc.

Lead Center

A number of recommendations have been made for establishing a lead center type organization somewhere in the field. This arrangement can be used with a NASA center or a new organization. Important advantages include; centralized management, avoidance of politics, lower cost of living, and a stronger technical staff. Many interviews identified Washington as a problematic location for such an office. The Space Station Reston office is identified as an example of Washington based problems such as high cost of living and Washington political duties siphoning off resources from technical activities. An organization located in a less congested area with lower cost of living will have greater success recruiting highly qualified technical personnel.

Using a NASA lead organization in the field (assuming NASA is the lead agency) is the traditional approach in NASA, at least prior to Space Station's Reston. Many in the agency believe this is the best way to manage a NASA program. This structure allows the management office to have ready access to a center's technical talent to work systems analysis and integration issues. This setup has both strong proponents and opponents. Several ex-program managers recommended using a lead center in NASA. The Aerospace Industries (AIA) recommended a straight forward management concept with a clear focal point, possibly a lead center. One respondent, in reference to questions about competition between centers, said that centers wouldn't cooperate with one another.

"Super" Program Office

Another option might be to create an Administrator's level program office. Here, a program office one level higher than other programs would provide cross organizational management and direction. The program manager could have "deputy administrator" status and thereby better enforce decisions across the agency and between agencies. This high level of authority would be especially valuable due to the breadth of program requirements involving nearly all NASA organizations. Additional advantages include providing high visibility, minimal disruption of current organizational structures, and a demonstration of the Administrator's support for program. However, this option does little to fix problems of the current infrastructure and would likely create dissension with other programs.

Board of Directors

Another option is to establish a board of directors comprised of high level representatives from each participating agency. The Board would serve a management coordination function. The advantage of a board available for arbitrating disagreements might be outweighed by the likelihood of high level lack of consensus and weakened management discretion.

Skunk Works

A "skunk works" type organization is an option based on small size and strength to move a program quickly and efficiently. Kelly Johnson created the first "skunk works" at Lockheed in 1943 to build the first U.S. fighter plane to fly faster than 500 mph. Many of Johnson's operating rules can be applied to several of the management options; restrict in almost a vicious manner the number of people involved, minimize required reports, contractor must be delegated and accept greater than normal responsibility, funding must be timely, and specs applying to hardware must be agreed to in advance of contracting. Although usually used for new start projects, such an organization, located close to an existing R&D center could also provide long-term focused management required for SEI.

Lowell Wood recommends chartering a small ad hoc organization specifically for developing (in his case) the Great Exploration program. This type of arrangement might be described as a "skunk works" where the staff is separated from many of the typical influences and interferences of older, more permanent organizations. This is similar to the possible use of a temporary commission as described in the Marshall Institute report, "to act as a governing and assessment body during the implementation of the program." Many fear that permanence automatically leads to less innovation and more bureaucracy.

National Program Office

A national program office was recommended by the DOD Blue Ribbon Committee as a management structure to provide better coordination across the agencies. The office would require access to a strong systems engineering staff, either civil service or contractor. The office could be a part of NASA, perhaps with a program manager who also served as a deputy administrator at NASA to assure agency-wide program and budget authority. If the overall SEI budgets passed through this office, its management authority would be enhanced. A NASA program office already has most of the required expertise for a manned space program. On the other hand a national program office can be outside of NASA and report to several agencies or to an entirely different agency. A completely clean slate is a great advantage to be weighed against such disadvantages as redundancy and competition with NASA; waste of current capabilities, costs of developing new capabilities and relations with NASA organizations. Again, a single point for SEI budgets would be preferable.

Satellite Organization

Some discussions at NASA identified creation of a small, autonomous satellite organization as an alternative, similar to special purpose organizations such as Saturn Corporation and Cray Computers. Such an organization could have total development responsibility. A satellite would be accountable to NASA (or any lead organization) yet separate from the normal agency structure. The satellite organization would probably be private sector, with that sector's inherent advantages. Here, many of the problems associated with large organizations in general and government in particular are avoided. Focus of purpose, flexibility and innovation can be nurtured while bureaucracy and lethargy are held at a minimum. Adopting such a structure offers a dramatic new way of doing business, while not radically changing NASA. Disadvantages include potential lack of support from traditional organizations, erosion of best talent from other organizations, start-up difficulties, and distrust of other agency employees.

JPL-like GOCO

Perhaps as the NRC suggests in its review of the 90 day study, "a new federally supported center in the mold of Bellcom, the Jet Propulsion Laboratory, the Mitre Corporation, or the Aerospace Corporation may have a role to play..." The DOE laboratories are good examples of quasi-government organizations success in employing high calibre employees in innovative environments. General Abrahamson of the DOD blue ribbon panel, reportedly felt that SEI should be managed by a new JPL type of organization. Many, including some on the Augustine committee, feel GOCO's (government owned, contractor operated) facilities have great advantages that need to be considered for the current NASA and future programs.

The GOCO organization offers considerable advantages for management autonomy and flexibility, environments conducive to innovation, flexible administrative procedures and attractive personnel compensation flexibilities, and better capability for keeping good employees and letting poor ones go. An article in Research Technology Management, October, 1989, "Bureaucratization in the Laboratory," identified some values of private operations. Research showed total levels of red tape in industrial and university labs were about one-third that of government labs. And, government labs averaged a six month wait before approving moves into new research. Some disadvantages include potential drift of high quality employees from non-GOCO centers and headquarters, higher costs, potential loss of control, difficulties of conversion, management spending less time technically and more time in administrative management (possibly an advantage), and possibly resistance of employees. Reportedly, NASA is currently studying the management option of Federally Funded Research and Development Centers (FFRDC), which have essentially the same basic components as a GOCO.

The Manhattan Project and the subsequent organization of DOE labs provide examples of the success of operating R&D facilities through university or not-profit organizations. The Manhattan Project leaders deliberately chose to avoid working through civil service establishments. Ironically, those same civil service inflexibilities are often cited today by many as the major impediments to NASA's current and future success.
n office.

A Strong Leader

Whatever organization structure is chosen will require a strong leader according to nearly everyone interviewed. All ex-program managers from NASA, including Hans Mark, insisted that the program needs a strong and committed leader to force decisions through the organizations. Mark recommended that the individual should hold a responsible post in all agencies involved. An ex-NASA manager said a strong manager would be able to stop competition between agencies and between centers. A Space Council staffer suggested a "dual hat" NASA manager, with specific positions in each agency, would be most successful. Although it is common sense, everyone agreed the program manager can either make or break the program. As Jim Herrington said, "everyone now (since Challenger) is scared of management risk...you need strong managers. Break the program into small projects, give them policy, money, and let them manage!"

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